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# Three Approaches to Mathematical Models for Finnish Natural Resource Management

Jukka Peltola

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# Three Approaches to Mathematical Models for Finnish Natural Resource Management

Jukka Peltola

DISSERTATION FOR THE DEGREE OF
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# Three Approaches to Mathematical Models for Finnish Natural Resource Management

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DISSERTATION

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## Abstract

With the Kyoto protocol and scientific evidence mounting, the debate on how to mitigate greenhouse gases has intensified. In Finland, many have questioned whether the agricultural sector could reduce it's share of greenhouse gases by using biomass energy as a replacement for fossil fuels. The first of these three essays investigates whether and under what conditions biomass energy production on Finnish agricultural land could be justified.

The other two essays are more general studies on the incentives of landowners in growing and managing energy and other crops. The second essay introduces an approach that disentangles risk and intertemporal preferences of a private entrepreneur's management decisions. Finally, the third essay uses modern programming methods to develop insights into a farmer's decision making.

The first essay deals specifically with the question; how to divide up the agricultural land for alternative uses (food production and biomass energy production) and how much nuclear power to produce. It is shown that when pollution is any concern, the biomass could be one suitable energy alternative. A clear land pressure between food and biomass energy feedstock production is also demonstrated.

In the second essay, a forest owner's utility is modeled using the recursive preference approach. The approach allows a researcher to disentangle risk-aversion and intertemporal substitution, and thus it provides policymakers with new information. The recursive preference approach is a special case of expected utility formulation, and therefore, it enables the outcomes from these models to be easily compared. According to the analysis, risk aversion seems to have an insignificant effect on management profiles. Instead, intertemporal substitution has a profound effect, further strengthened when the intertemporal elasticity of substitution is low.

The third essay is an application of mathematical programming to help shed light on a farmer's decision making process. The positive mathematical programming (PMP) is used to calibrate a mathematical model to a multiyear data set, and maximum entropy (ME) is used to determine cross-effects of different activities in a cost function of a farmer. The program performance is tested out-of-sample on different levels of data aggregation. The main findings are that the model performs well, and the ability to use more detailed data produce better results in calibration. However, with this particular data, the better calibration fit does not translate to significantly better forecasting results.

Professor Richard E. Howitt
Dissertation Committee Chair

This is dedicated to my mother and father,

Laura and Pentti Peltola

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# Essay 1

# Energy Production and Land Allocation with Multi-type Pollution

This essay has two emphases, first, to evaluate an optimal land allocation between food and biomass energy production and secondly, to look at nuclear power production as an alternative energy source. My main concern here is on the particular types of pollution stemming from these energy sources, and how these two types of pollution affect differently societal welfare. Natural resource scarcity is not an issue here.

Biomass energy and coal power generation produce $CO_2$ effluents and nuclear power production results in radioactive byproduct. "Surplus" $CO_2$ as a greenhouse gas can be considered a common nuisance, where the nuisance level increases with stock. The radioactive waste stock is assumed not to significantly affect the human population until it reaches a particular (random) threshold level. After reaching the threshold, the nuclear waste will cause a catastrophic effect. I investigate this as an optimal control problem, with two waste stocks, one affecting the maximization deterministically, another probabilistically. After that, I provide (necessary and) sufficient conditions for the stability of the steady state. Finally, I complete the analysis by calculating and interpreting the steady state comparative statics and dynamic envelope results.

In the study, conditions for the stability of the steady state are found. These conditions are reasonable and intuitively acceptable. In the subsequent sensitivity analysis most of the comparative static and envelope results can be signed, and these results follow an economic intuition too. The study shows that under quite realistic assumptions it would be sensible to use part of the agricultural land for energy production.

## 1.1 Introduction

In this study, I will compare two energy production alternatives with different pollution characteristics. The analysis was prompted by a recent public debate in Scandinavian countries about suitable energy sources for the future. In the process of ranking alternative energy sources, pollution generation has become increasingly important, whereas natural resource scarcity does not seem to be as topical. For example, fossil fuels like oil and coal, are now mainly blamed for the pollution they produce, especially for effluents of carbon dioxide ($CO_2$) which is one of the most well known greenhouse gas. The exhaustability of fossil fuels does not seem to be such an acute fear any more. This has prompted comparisons of carbon based i.e., $CO_2$-effluent producing energy sources and nuclear power, both of which seem to have an ample resource base, but cause some pollution.

The current discussion about the appropriate energy source has been going on in Finland since the eighties. Energy intensive paper, pulp and sawmill industries have been the most important industries in the country, and therefore, an inexpensive power source is considered to be crucial. Unlike its nordic neigbhours, Finland does not have significant water resources for the production of hydropower, nor has she oil or coal. Four nuclear power plants have been filling large part of her energy needs since the seventies. Industry lobbies have been promoting building a fifth nuclear power plant over the past ten years. The lobbying has been intensifying since the meeting of world countries in Kyoto 1997, where participants agreed on a common agenda for managing carbon effluents in the future. The proponents of nuclear power have interpreted the Kyoto agreement to mean that nuclear power is the only acceptible large scale energy alternative in the future. Opponents see nuclear power production extremely negative for two reasons: first, there are risks of catastrophy in production, and second, problems exist in handling nuclear waste. The energy discussion in Finland has been polarized by these two groups whose main arguments are based on the different pollutive nature of these energy sources.

In this paper, I set the discussion into a more general framework by analytically comparing nuclear power and a $CO_2$ producing energy choice. The $CO_2$ producing alternative here is biomass energy, based on agricultural crops or woody crops. The purpose is to look at energy choice and agricultural land allocation for raw materials for energy production and for food. After finding general conditions for the stable equilibrium to exist, I investigate effects resulting from changes in model parameters. I construct a stylized model consisting of a social planner who designs a policy for a hypotethical state where only energy and food are consumed. As a source of energy, the planner may choose nuclear power or a $CO_2$ producing alternative, in this case biomass energy. The fossil fuel utilization always releases the carbon content of the fuel into air when the fuel is burned. On the other hand, the $CO_2$ producing alternative is based on biomass. Biomass production captures minerals from earth, carbon from the air, and utilizing sun light produces energy feedstock. In the growth process, plants assimilate carbon from the atmosphere which is released back to the atmosphere when the plant biomass is utilized for energy. A whole production chain has some positive net effluents due to transportation and processing. This is true even if one assumes that in the production chain activities of biomass energy feedstock production and energy processing have a zero net carbon outflux. The system resembles waste recycling. Just like in recycling, nothing can be recycled 100 percent, and therefore, even in a case where energy production is fully based on biomass energy, the net carbon outflux is positive.

In the model, I concentrate on biomass energy which causes carbon emissions into the atmosphere. Nuclear power production is carbon-free, but causes probabilistic accidents and subsequently radioactive pollution with its known problems. Built in the model, atmospheric $CO_2$ causes a nuisance, which is positively related with its stock size. Radioactive waste does not generally cause any disutility, but may probabilistically cause a catastrophic event which drives the utility to zero instantly after the event. This construction accounts for the most important perceived differences in the usage of the aforementioned power sources. To keep the system simple and analytically tractable, natural resource scarcity is not included in the model.

The paper begins by a brief description of the situation in Finland. First, the debate between the different groups is described. Thereafter a brief look on the seminal papers on growth models with pollution is taken. Next, a model is described. A two stock optimal control model with stock and flow pollution is set up. This is followed by determining the necessary and sufficient conditions for the stability of the local steady state. Finding reasonable conditions for stability proves that an energy mix utilizing some biomass energy is theoretically possible in a situation described by the model. Furthermore, the results from the stability analysis are later used in sensitivity analysis. A summary and conclusions are presented in the final section.

## 1.2 The Setting in Finland

In Finland, energy intensive industries have for a long time been lobbying for the building of a fifth nuclear power plant. In the last 15-20 years, building of the fifth reactor in Finland has been discussed occasionally and the discussion has recently heated up again. A significant difference between the current and earlier debates, is that in the most recent one, the nuclear power is actually promoted as clean energy, and the competing coal (and biomass) energy is blamed for its carbon emissions causing global warming[1]. The $CO_2$ effluents and subsequent climate change is a convenient argument for using nuclear power since it does not produce CO2 effluents.

[1] Of course some carbon exists in the atmosphere naturally. However, if the concentration of the atmosphere changes, it may trouble world ecosystems as biological systems require considerable amount of time to adjust to a new carbon concentration level. Commonly, the carbon level before industrial revolution has been used as a baseline.

The European Union (EU), with its directives, and global climate change agreement in Kyoto are used to support the nuclear power case with remarks such as "We have to adjust to these international guidelines and the only "choice" we are left with, is to use practically carbon free nuclear power". With this kind of argument, proponents of nuclear power are attempting to hide behind a larger authority and are trying to avoid getting tainted in the process themselves.

The Finnish Energy Strategy adopted by the Government of Finland (Anon. 1997) also emphasizes the need of reducing the CO2 effluents. Oftentimes nuclear power with resulting carbon effluent reduction and coal power with large carbon effluents are considered and presented as the two main alternative energy sources (HS 1997a). The official energy strategy of the state is carefully written such that it does not emphasize any energy alternative over another, as there has been strong political sentiments on the topic in recent times. At the moment the nuclear power supporters are staying behind the scenes and waiting for the right time before getting into a public debate. The most recent talks about the fifth reactor are not proceeding due to strong public opposition. Supporters are waiting for the possibility to officially demand that the government follows the international effluent agreements, and in that way, pressure the state to authorize the construction. The industry groups emphasize the environmental issues, international trade issues, and profitability of the larger energy production units on the new, international electricity markets, which allow more freedom for power management and in that way support using of larger units. Of the large political parties, the conservatives strongly support expanding the nuclear reactor fleet, the Social Democratic Party seem to have some support on the topic whereas in the Center Party there are conflicting views about a new nuclear plant. The Green Party and the Christian Party are also against the construction. Finally, the largest labor unions support adoption of additional nuclear power (HS 1997b).

In the discourse, there can be found some strategic elemets as well. Herne (1994 pp. 41-56, 1997 pp. 122-123) describes a Finnish national power strategy discussion at the beginning of the 90's as a public discourse[2]. Herne (1994) analyses 143 arguments for and against nuclear power where three alternatives, nuclear power, coal power and bioenergy (and some other smaller energy sources) are mainly discussed. The author observes, that two or three alternatives at the time, combined or separately, are used according to a point of view and a goal of the argument. For example, a supporter of a nuclear power would evaluate two different dimensions of energy policy choice using only two of the three energy alternatives at the time: the agent may for example

[2]In the study Herne takes a modern decision theory point of view in order to analyze how irrationality affects individual decision making. The main emphasis is on irrationality which shows as violations against axioms of expected utility theory, or in more detail, on preference reversals due to framing effects and manipulations of the choice sets. As an example, the author takes the Finnish energy discussion concentrating on behavior of supporters and critics of nuclear power and concludes that an asymmetric domination was used in manipulation of the choice set.

compare nuclear power and coal power to emphasize the environmental friendliness of the nuclear power. The bioenergy would be left aside in this kind of an argument. In another argument the reliability of a power source could be looked at by combining nuclear power and bioenergy alternatives as this emphasizes the relative reliability of the nuclear power. In this context the coal power option would be left aside. In this manner asymmetric domination can be used to manipulate opinions by utilizing inconsistencies in human choices and decision making. The analyses shows clearly how nuclear power is set against the two other alternatives, one at a time.

Besides reliability, economic, and political arguments, the main environmental arguments are that coal power produces a large environmental damage with somewhat known consequences, and nuclear power production could probabilistically cause (with a small probability) a very large damage with unknown consequences. In some arguments bioenergy is summed also together with coal power as a source of $CO_2$. This seems somewhat goal-oriented, for in practice, the carbon cycle in bioenergy production differs considerably from that of a fossil fuel alternative. The carbon economy of a bioenergy system is rather a way of recycling carbon dioxide, with very low net emissions. Therefore, it should not be compared to fossil fuel system, where carbon is continuously released into atmosphere and assimilation is relatively low. All in all, the situation in Finland is currently such that about 35 percent of the people support expanding the nuclear power and a somewhat lower percentage of the people, 30, is clearly against. Natural gas is the most favoured energy source; about 70 percent of the Finns would like to increase its usage. However, the main industrial lobbies support the nuclear power, and of the political parties only minority seems to be clearly against it. Therefore, over 56 percent of the people believe that additional nuclear power will be built in any case (KU 1997).

In Sweden, on the other hand, a very different policy has been followed. The government there made a political decision a couple of years ago to end nuclear energy production in the country by the year 2010. Some political and economic incentives have been created in order to make biomass energy, reseach, and production more commercially interesting, and in that way produce a "backstop" technology for fossil fuels and nuclear power. However, this has caused more discussion about a role of biomass energy in creating greenhouse gases, especially $CO_2$. In recent years, Sweden has also been struggling with recession and high unemployment, and subsequently it has been questioned, if the decision to end the nuclear power era there was made too hastily. It has been suggested that the decision should be reconsidered, for in some circles nuclear pover is seen to be internationally a more competitive energy source. Some nuclear power supporters in Finland have also been questioning the stability and reliability of the decision by Swedes to end the nuclear power production as it is seen to cause such high adjustment costs for domestic industries in the short run (HS 1997b).

As the lively exchange shows, there is considerable general interest on energy issues in Finland at the moment. From a practical point of view, the following study will serve as structuring comparisons between different alternatives. The study clarifies the differences between the alternatives energy sources according to their pollutive characteristics as this is seen as one of the main arguments in the debate.

## 1.3 Literature on Energy and Pollution

In the 1960's and 1970's, there were several doomsday scenarios on resource scarcity presented by scientists which alarmed both politicians and common public. The discussion was very simplistic concentrating only on physical stocks and flows. Economics of a social system e.g., price signals were not taken into account. This caught the attention of economists, which began to investigate the interface between resources, pollution and the behavior of the firms, industries, and the economy (Solow 1974). One of the early papers in the evironmental economics field is written by Forster (1972), who looked at the role of pollution in traditional growth models. According to his study, even if pollution is not controlled, the economy may equilibriate, i.e. both, amounts of capital and pollution may end up in the steady state amounts. However, in general the resulting steady state may not be optimal, and in order to reach another, "preferred" solution, the society may need to devote some resources to pollution control.

Another pioneer is Smith (1974), who concentrated on the optimal extraction of exhaustable natural resource stock (e.g. coal or oil). Although Smith does not account for a pollution by-product, the paper is technically similar to Forster's. The main question addressed by Smith is how to allocate labour between production of exhaustable, low-cost energy type and renewable, high-cost energy type. The phase diagram is used for the analysis, which has three main possibilities i) all solar energy, ii) both solar and fossil fuel, and iii) all fossil fuel based energy. In the model, production technologies have constant returns to scale and discounted output is maximized. As an extension the author looks at three cases: i) diminishing returns in backstop energy production, ii) discounted utility maximization, and iii) decreasing returns to scale in mining.

Cropper (1980) extends the above model by accounting for pollution. In her model the fossil fuel is mined from an exhaustable stock, and usage of nuclear power increases the radio-active waste stock. This model has naturally two state variables and 2(3) control variables. The first version of the model simply allocates labor (land) either to nuclear or to solar energy production. The second model includes three control variables dividing the allocatable input between the two productive purposes and a third clean-up activity, which decreases radio-active waste creation in nuclear power production. The key questions addressed in Cropper's study are: i) what effect breeder fission has on the rate of depletion of fossil fuels and, ii) how the path of nuclear energy production changes over time.

In an earlier paper Cropper (1976) evaluates the nuclear energy alternative in the case where a catastrophic nuclear accident is possible. According to the author, the paper concentrates on the most typical pollution aspect in the nuclear power production, namely, it attempts to capture the "small probability of large loss". The paper clarifies the analytical differences of catastrophic pollution compared to a common nuisance pollution. As a result of the differences, Cropper finds the existence of both cases: multiple equilibria and no equilibrium. The same model is then applied to natural resource management where a particular management strategy may push the stock to extinction.

Qualitatively similar point of views have been recently discussed in an empirical paper by Anderson and Bird (1992). The authors analyze the carbon taxes as an incentive to decrease $CO_2$ flux in the atmosphere and suggest that such taxes may promote adoption of renewable energy sources at the cost of fossil fuels and nuclear power. In the paper, they emphasize the land allocation question. The authors also look at competing land uses and their effect on the biomass energy production potential. Similar modeling approaches are found in the literature, for instance, the work by Huhtala (1995) in case of recycling and by Tahvonen (1989) in case of renewable resource harvesting

In the current model, I investigate the production of energy using nuclear power or biomass. There is assumed to exist abundant amount of both of these fuels and therefore the traditional cost of production is not important. As a result, I am able to concentrate on environmental (i.e. pollution) costs alone. Whereas the papers by Cropper look at the catastrophic event and nuisance stock creation separately, I combine these two approaches into a single model. By combining them I can bring out the issues emphasized above, namely, the differences in pollution. The basic question in this model is how to optimally divide the land between food and energy production where one receives utility from food and energy consumption. Besides the land allocation desicion, there is another control variable: the amount of nuclear power utilized. Potentially, a clean-up activity could be added, thus as a third control decision would be the division of produced energy between consumption and radioactive waste clean-up.

To reiterate, the main questions addressed in this paper are: *1) how to allocate agricultural land between food and non-food (energy) production*, and *2) what kind of combinations of nuclear power and solar energy would be used over time*, and *3) how the system is affected by model parameter changes.* One may think of the energy production as the main activity in the model while food production is essentially capturing the opportunity cost of land allocation. The uncertainty modeled here stems from the unknown natural threshold, which causes a catastrophy to occur. Therefore, this model can be called an endogeneous uncertainty model according to a categorization of Tsur and Zemel (1996, 1997).

## 1.4 The Formulation of the Model

The model describes a situation where an agent receives utility from both food and energy consumption. To satisfy the consumption needs two alternative energy sources can be utilized: nuclear power or biomass energy. Both energy sources cause some pollution, namely radioactive waste and carbon dioxide respectively. Neither type of pollution is taxed. Furthermore, the model is a "large country" model meaning that the possible trade effects and influx of foreign pollution are assumed to be insignificant.

We assume that there is no continuous out-flow of radioactive pollution, as the radioactive fuel is generally well-managed. The radioactive pollution only harms us as a result of an accident. An accident is assumed to be sudden and dangerous, where the probability of an accident increases as the usage of nuclear energy grows. The catastrophic event from radioactive pollution potentially causes a discrete drop in utility where the utility after the event is zero. Another type of pollution, in the form of carbon dioxide, comes from biomass energy. As discussed earlier, the net carbon outflux from biomass energy is assumed to be always positive, even if small. This is built into the model such that using bioenergy causes the surplus $CO_2$-stock in the atmosphere to increase. The surplus carbon causes continuous damage (nuisance), which is positively related to the size of the carbon stock which is in turn determined by the carbon effluents.

While the basic construction of the model follows the approach of Cropper (1976), it differs in two major ways: *i)* besides the nuclear waste accumulation, the model allows "competing" pollution", $CO_2$, and *ii)* the main interest lays in the resulting land division between food and non-food production, not in labor allocation. The interest here is the land use in a case where food production and energy production are competing land utilization systems.

I address this problem of determining an optimal land allocation between energy and food production as an optimal control problem. In any optimal control program, a temporal development of the system is described by state variable(s), which in this analysis are $W$ and $S$, the nuclear waste stock and carbon dioxide stock, respectively. The social planner, by optimally adjusting the control variables, land allocation and nuclear energy production, affects the level of the state variable, and thus the evolution of the whole system.

The program to be maximized is written out below. In the program an agent receives utility, $U(C, F)$ from (energy) consumption ($C$) and food consumption ($F$). Food consumption equals food production, which is determined by the acreage allocated to food crops, $F = \gamma L_F$. The utility function is assumed to be continuous, concave, and twice continuously differentiable. Neither type of pollution enters into the utility function itself, but instead $CO_2$ -surplus stock and nuclear waste stock enter through a convex damage function, $R(S)$, and probability measure, $\Lambda(W)$, respectively[3]. The parameter $\varrho$ is a scaling parameter for carbon based disutility, reflecting a different vulnerability of different countries and regions to climate change.

$$
\begin{aligned}
Max\ J[W, S, L_E, L_F, N] &= \int_0^\infty [\Lambda(W)U(C, \gamma L_F) - \varrho R(S)]e^{-rt}\, dt && (1.1)\\
s.t.\ \dot{W} &= G(N) - \varphi W\ ;\ W(0) = W_0 && (1.2)\\
\dot{S} &= \alpha f(L_E) - z_1 L_E - z_2\ ;\ S(0) = S_0 && (1.3)\\
C &= E(L_E) + N && (1.4)\\
L_E + L_F &= \bar{L},\ L_E\ \geq 0,\ L\ \geq 0,\ N \geq 0 && (1.5)
\end{aligned}
$$

This is an infinite horizon autonomous optimal control problem. Autonomous basically means that time $t$ does not enter explicitly into the integrand or state functions. The system can be simplified by assuming an interior solution. In the present case this means that control variables are assumed to be positive. As a result, the system can now be called a *simplified control problem.*

In the model, the consumption decisions are satisfied by allocating the total amount of agricultural land ($\bar{L}$) into two competing uses, namely energy production ($L_E$) and food production ($L_F$). Besides biomass energy, nuclear power ($N$) may be used for energy production, however this process always creates nuclear waste ($W$) as a by-product according to a function $G(N)$, where $G'(N) > 0$. If the nuclear waste stock reaches a certain, random treshold level, it causes extensive damage, otherwise it does not affect utility in any way. Radioactive waste decays extremely slowly over time at rate $\varphi$. Thus the problem is somewhat similar as in the extraction of exhaustable resources, just that now one is filling a mine, not emptying it. The consumption function is linear in both, biomass energy and nuclear power: $C = E(L_E) + N$. One could argue, that useage of electricity produces e.g. some sort of network externalities, at least in some consumption levels, and therefore consumption could alternatively be modeled increasing in electricity useage. However, for simplicity, a linear form is used. Similarly, biomass electricity production as a function of land use, $E(L_E)$, is assumed to have a linear relationship. As our main objective is to evaluate effects of different type of pollution energy usage and land allocation, the simple linear structure serves the purpose well.

In biomass energy utilization (e.g., when burning wood) biomass energy production releases $CO_2$-flux in the atmosphere. This is described with a function $\alpha f(L_1)$. On the other hand, the biomass growth process assimilates carbon from atmosphere $z_1 L_1$. In an ideal case the two flows were in balance, but in practice this is not a case. When accounting also for biomass transportation and processing, and energy consumption, the net effluent is positive. Therefore, the total net effluent from biomass energy, calculated per-hectare basis is always positive:

$$\alpha f(L_1) - z_1 L_1 > 0. \qquad (1.6)$$

[3]The assumptions about the probability are essentially the same as the ones used by Cropper (1976), and therefore $\Lambda(W) = \int_W^\infty g(W^*)dW^* \geq 0$ and $\Lambda_W = -g(W) \leq 0$ and $\Lambda_{WW} = -g'(W)$.

The carbon accumulates in the $CO_2$-surplus stock and causes a nuisance directly related to the size of the stock.

Besides the carbon relieved from biomass or fossil fuels by human activity, there exists a natural base level carbon cycle from plant growth and decay in nature. Due to a base level carbon cycle, there is a significant carbon influx and outflux in the atmospheric carbon. Therefore, one can think of the management of this stock as the management of a biological asset essentially comparable to the management of a renewable resource, without reproduction. In the model, the amount of $CO_2$ in the atmosphere depends on two things: carbon "catchment" by activities in socety and carbon "catchment" by the nature. The first one, described above, reflects the energy biomass growth on agricultural land (i.e. recycling of carbon in the biomass energy feedstock growth process). The second one stands for all "other" catchment, for example carbon accumulation into growing forests or into seas. This flow is described by single parameter, $z_2$.

In the model, I set up so called Inada conditions, mathematically written as $lim_{L_F->0}U_{L_F} = \infty$, $lim_{C->0}U_C = \infty$. These conditions signify the fact that if one has near zero amount of something, any additional amount increases one's utility considerably. Inada conditions are sufficient for an interior solution to exist. In the case of food, the above condition means that when food acreage is very small, the marginal utility of land in food production is very high. Similarly in the case of energy, the condition for consumption says that when energy consumption is close to zero, the marginal utility of energy is very high. These conditions guarantee that the variables $L_F$ and $C$ are always positive, thus no explicit nonnegativity constraints for these are needed.

In order to solve the simplified control program, I rewrite the system in the Hamiltonian form. The Hamiltonian is a particular way of writing the objective function and the equation of motion together such that the system is easier to work with. To achieve somewhat a simpler mathematical form, the present value Hamiltonian is transformed to a current value form. This means that the value of the maximization program and the shadow value are not discounted back to time zero, but instead the discussion of the problem as well as its interpretation are in terms of current values i.e., $t = s$. Additionally, substituting $L$ for $L_F$, and $(\bar{L} - L) = L_E$, and then writing $E(\bar{L} - L) + N = C$, the Hamiltonian in the current value form appears as follows:

$$\begin{aligned} Max_{(L,N)}\ H = \Lambda(W)U(E(\bar{L} &- L) + N, L) - \varrho R(S) + \eta[G(N) - \varphi W] \\ +\lambda[\alpha f(\bar{L} &- L) - z_1(\bar{L} - L) - z_2]. \end{aligned}$$

In order to solve the optimal control program one needs to derive the necessary conditions. This can be done by invoking the theorem 3.12 by Seierstad and Sydsäter (1987). According to the theorem, the necessary conditions are as follows:

$$\frac{\partial H}{\partial L} = \Lambda(W)[U_C C_E E_{L_E} L_{EL} + U_L] + \lambda(\alpha f_{L_E} L_{EL} + z_1) = 0 \qquad (1.7)$$

$$\frac{\partial H}{\partial N} = \Lambda(W)U_C C_N + \eta G_N = 0 \tag{1.8}$$

$$\dot{\eta} = \eta r - \frac{\partial H}{\partial W} = r\eta - \Lambda_W U(\ ) + \eta\varphi \tag{1.9}$$

$$\dot{\lambda} = r\lambda - \frac{\partial H}{\partial S} = r\lambda + \varrho\frac{\partial R}{\partial S} \tag{1.10}$$

$$\dot{W} = G(N) - \varphi W \tag{1.11}$$

$$\dot{S} = \alpha f(\bar{L} - L) - z_1(\bar{L} - L) - z_2. \tag{1.12}$$

The first two of the above conditions are the *simplified Maximum Principles.* The equation (1.8) is affected by land allocation through bioenergy and food consumption decisions. It says that the probabilistic utility from land must be equal the external cost from biomass energy use weighted with the shadow value $\lambda$. The equation (1.9) is the same type of condition for nuclear power consumption. According to that, it is required that (probabilistic) benefits from nuclear power usage must equal to (indirect) harm caused by the nuclear waste stock increment. The equations (1.10) - (1.11) are *the co-state equations* for the nuclear and carbon stock respectively. Finally, the last two equations, (1.12) - (1.13), are *the state equations*, also called the equations of motion. The equations (1.10) - (1.13) as a group are called *the canonical equations.* Noting that $C_E = C_N = 1$ and similarly $L_{EL} = -1$ the Maximum Principle equations may be simplified as:

$$\tfrac{\partial H}{\partial L} = \Lambda(W)[-U_C E_{L_E} + U_L] + \lambda(-\alpha f_{L_E} + z_1) = 0 \tag{1.13}$$

$$\tfrac{\partial H}{\partial N} = \Lambda(W)U_C + \eta G_N = 0 \tag{1.14}$$

More information of the system can be extracted by rearranging and reducing the above necessary conditions. Using the co-state equations, it may be shown that if $\lambda$, the shadow price of the $CO_2$ stock, is assumed to be highly negative to begin with, it will never go positive. Similarly, to sign $\eta$ the equation (1.15) is used: $-\eta = \Lambda(W)U_C/G_N$. It is known that the right hand side is positive, thus $\eta$ must be negative. The same result for the steady state can be reached using the co-state equation (1.10). At the steady state, $r\eta - \Lambda_W U(\ ) + \eta\varphi = 0 \ \Rightarrow\ \eta = \Lambda_W U(\ )/(r + \varphi)$. Knowing that $\varphi > 0$ and similarly $\Lambda_W = -g(W) < 0$, it may be seen that the shadow value of the radio active waste stock is negative. Cropper (1976) interprets this shadow price of radioactive stock as a cost in the future, or as a decrease in the future utility caused by an increase in the nuclear waste stock.

Additionally, the necessary condition (1.14) may be written as $\Lambda(W)[U_L - U_C E_{L_E}] = \lambda(\alpha f_{L_E} - z_1)$. As discussed above (equation 1.6), the $CO_2$ effluents from biomass energy production may be taken to be small but never negative, therefore $(\alpha f_{L_E} - z_1) > 0$. As the probability, $\Lambda(W)$, is always positive. One may conclude that $(U_L - U_C E_{L_E})$ must be the same sign as $\lambda$ i.e., it must be negative. This appears to be useful later in the comparative statics analysis.

Several points about the model may be noted at this time. In general, when the pollution is the only cost of energy use, one would suspect that if effluents are decreased for whatever reason, then the use of that energy type increases. For instance, for a larger decay parameter, the use of nuclear power is expected to increase. Similarly, if $z_1$ increases, the use of biomass energy should increase. An effect from an increment in land area does not appear as clear. One might expect, that the extra land would be divided between the two uses in the same proportions as the land already available. These intuitive propositions will be tested later in the sensitivity analysis section.

## 1.5 The Local Stability of the Steady State

A natural next step is to prove the local stability of the assumed steady state. The stability conditions tell us what is required for the developed model to have a stable steady state or if it is even theoretically possible to reach the steady state. The stability analysis can be done by studying the above canonical differential equation system. For determining the conditions for local stability, one may use a theorem developed by Dockner (1985). This is a convenient way to proceed, as in the process one also determines short run comparative statics results (SRCS)[4]. Later the results from the stability analysis may also be used in determining other sensitivity results. In the following, the first two of the above six equations are taken, and they are used in order to rewrite the control variables as functions of states, co-states and parameters. Then the control variables in the canonical equations are replaced by these functions. Thus the number of equations to be evaluated is decreased to four. By evaluating these four equations, one may determine the conditions for the local stability.

As discussed in the literature (Dockner 1985), the system of canonical equations is characterized by a general instability property, thus the most that can be expected is conditional stability in a saddlepoint sense. Practically this means that initial conditions are crucial: if the initials conditions belong to a certain subset, it is possible to reach the steady state. To determine the conditions needed for stability, I use Dockner's main result (Dockner 1985). In words, I have to show that a determinant of the certain Jacobian is positive, $|\mathcal{J}| > 0$ and a linear combination of three other determinants is simultaneously negative, $\mathcal{K} < 0$ (see below the equations 1.38 - 1.39). In the process, the system of equations are first linearly approximated and then evaluated at a steady state. Therefore, the stability conditions apply only locally and to a linear approximation of a two state variable non-linear system[5].

[4]Short run comparative static results are evaluated in this section as part of the stability analysis. However, the results are reported in the next section together with other sensitivity analysis.

[5]Furthermore, if one is interested to know whether the existing roots for the problem are real or imaginary, one may follow the method provided by Tahvonen (1989). To prove a stability of a

The technique proceeds as follows: First, the implicit function theorem is used on the equations of the aforementioned simplified Maximum Principles in order to write the control variables as functions of state variables, co-state variable and parameters. Then the first two necessary conditions are totally differentiated in order to find how perturbations in states and co-states affect control variables as if the states and co-states were parameters. As a byproduct, the process will reveal the effects on control variables from changing any of the exogeneous parameters. The results from total differentiation are as follows:

$$\begin{gathered}\Lambda_W(W)[U_C C_E E_{L_E} L_{EL} + U_L]dW + \\ \Lambda(W)U_{CC}C_E E_{L_E} L_{EL} dL + \Lambda(W)U_C C_{EE} E_{L_E} L_{EL} dL + \\ \Lambda(W)U_C C_E E_{L_E L_E} L_{EL} dL + \Lambda(W) U_E E_{L_E} L_{ELL} dL + \\ \Lambda(W)U_{LL} dL - \lambda\alpha f_{L_E L_E} L_{EL} dL - \lambda\alpha f_{L_E} L_{ELL} dL + \\ \Lambda(W)U_{CC} C_N C_E E_{L_E} L_{EL} dN + \\ \Lambda(W)(U_{CC} C_E E_{L_E} L_{E\bar{L}} L_{EL} + U_C C_{EE} E_{L_E} L_{E\bar{L}} L_{EL} \\ + U_C C_E E_{L_E L_E} L_{E\bar{L}} L_{EL}) d\bar{L} - \lambda\alpha f_{L_E} L_{E\bar{L}} L_{EL} d\bar{L} \\ -(\alpha f_{L_E} L_{EL} - z_1) d\lambda - \lambda f_{L_E} L_{EL} d\alpha + \lambda dz = 0 \end{gathered} \tag{1.15}$$

$$\begin{gathered}\Lambda_W U_C C_N dW + \Lambda(W) U_{CC} C_N dN + \Lambda(W) U_C C_{NN} dN + \eta G_{NN} dN + \\ \Lambda(W)[U_{CC} E_{L_E}](d\bar{L} - dL) + G_N d\eta = 0\end{gathered} \tag{1.16}$$

Now these equations can be reorganized into a matrix in order to determine the relationships between states, costates, and control variables (i.e., $Mx = Ry$), where the $x$ is the vector for the control variables and $y$ the vector for the states, co-states and parameters. The procedure can be done simply by invoking Cramer's rule. Noting that $C_E = C_N = 1$ and $C_{EE} = C_{NN} = 0$, and similarly that $L_{EL} = -1$ and $L_{ELL} = 0$, the matrix notation results in the following system:

$$\begin{bmatrix} \Lambda[-U_{CC}E_{L_E} - U_C E_{L_E L_E} + U_{LL}] + \lambda\alpha f_{L_E L_E} & -\Lambda(W) U_{CC} E_{L_E} \\ -\Lambda(W) U_{CC} E_{L_E} & \Lambda U_{CC} + \eta G_{NN} \end{bmatrix} \begin{bmatrix} dL \\ dN \end{bmatrix} = \tag{1.17}$$

$$\begin{bmatrix} CA & CB & \lambda f_{L_E} & -\lambda & 0 & CH \\ -\Lambda_W U_C & 0 & 0 & 0 & -G_N & -\Lambda(W) U_{CC} E_{L_E} \end{bmatrix} \begin{bmatrix} dW \\ d\lambda \\ d\alpha \\ dz_1 \\ d\eta \\ d\bar{L} \end{bmatrix}, \tag{1.18}$$

where $CA = -\Lambda_W[U_L - U_C E_{L_E}] < 0$ since $-\Lambda_W$ is positive. Similarly, as was discussed earlier, $CB = [\alpha f_{L_E} - z_1] > 0$ due to biological and technological factors in production process. The term $CH = \Lambda(W)[U_{CC} E_{L_E} + U_C E_{L_E L_E}] + \lambda\alpha f_{L_E}$ may

global steady state, one may use an approach by Sorger (1989 ).

be either positive or negative. The "cross terms" $-\Lambda(W)U_{CC}E_{L_E}$ are always positive. The first part of the equations describes the net marginal utility effect from agricultural land through food production and energy production. The second part describes the marginal utility-pollution effect due to the biomass energy production.

For Dockner's theorem to apply, the benefit function entering into the Hamiltonian was assumed to be concave. Therefore, by concavity of the program we know that for the matrix M: 1) the determinants of the first order principals must be nonpositive, 2) the determinants of the second order principals must be nonnegative. With this knowledge one can evaluate the sign of some otherwise ambiguous terms i.e., one now knows the signs of the terms on the diagonal: $-\Lambda(W)[-U_{CC}E_{L_E} - U_C E_{L_E L_E} + U_{LL}] + \lambda \alpha f_{L_E L_E} < 0$ and $\Lambda(W)U_{CC} + \eta G_{NN} < 0$.

By using Cramer's rule the sign of the terms below can be determined. These terms are needed in the process of finding the stability conditions. However, they are also short run comparative static results (SRCS), which show how the control variables change as a result of a change in states, co-states or program parameters.

$$\begin{aligned} dL/dW &>< 0, \quad dN/dW >< 0, && (1.19)\\ dL/d\lambda &< 0, \quad dN/d\lambda < 0, && (1.20)\\ dL/d\alpha &> 0, \quad dN/d\alpha > 0, && (1.21)\\ dL/dz_1 &< 0, \quad dN/dz_1 < 0, && (1.22)\\ dL/d\eta &> 0, \quad dN/d\eta > 0, && (1.23)\\ dL/d\bar{L} &>< 0, \quad dN/d\bar{L} >< 0. && (1.24) \end{aligned}$$

As the assumptions for Dockner's theorem are fulfilled, the implicit function theorem can be used, to rewrite the control variables as functions of the states, co-states and parameters.

$$L = \Psi(W, \lambda, \eta; \alpha, z_1) \tag{1.25}$$
$$N = \Phi(W, \lambda, \eta; \alpha, z_1). \tag{1.26}$$

After this, the control variables in the four canonical equations, (1.10) - (1.13), can be replaced by these functions, and thus the canonical equations in term of the states, co-states and parameters end up as follows:

$$\begin{aligned} \dot{\eta} &= (r+\varphi)\eta\Lambda_W U[E(\bar{L} - \Psi(\,)) + \Phi(\,), \Psi(\,)] && (1.27)\\ \dot{\lambda} &= r\lambda + \varrho R_S && (1.28)\\ \dot{W} &= G(\Phi(\,)) - \varphi W && (1.29)\\ \dot{S} &= \alpha f(\bar{L} - \Psi(\,)) - z_1(\bar{L} - \Psi(\,)) - z_2. && (1.30) \end{aligned}$$

Next, the Jacobian $\mathcal{J}$ for this *Modified Hamiltonian Dynamical System* can be derived. Note that the canonical equations are now written without explicit decision variables, that is, only as functions of the states, the co-states and the parameters. These four equations are totally differentiated and written in a matrix form, $\mathcal{J}x = \mathcal{Q}y$, in order to use the $\mathcal{J}$ matrix on the left hand side for the stability analysis and the $\mathcal{Q}$ matrix on the right hand side for the comparative static analysis. This differentiation results in the following system.

$$\begin{aligned}
\dot{\eta} &= j_{1\eta}d\eta + j_{1\lambda}d\lambda + j_{1W}dW + q_{1\alpha}d\alpha + q_{1z_1}dz_1 && (1.31)\\
&+ \eta r + \eta d\varphi + q_{1\bar{L}}d\bar{L} = 0 \\
\dot{\lambda} &= rd\lambda + \varrho R_{SS}dS + \lambda dr + R_S d\varphi = 0 && (1.32)\\
\dot{W} &= G_N\Phi_\eta d\eta + G_N\Phi_\lambda d\lambda + (G_N\Phi_W - \varphi)dW + G_N\Phi_\alpha d\alpha && (1.33)\\
&+ G_N\Phi_{z_1}dz_1 - Wd\varphi = 0 \\
\dot{S} &= MM\Psi_\eta d\eta + MM\Psi_\lambda d\lambda + MM\Psi_W dW + (MM\Psi_\alpha + f(\ )\ )d\alpha && (1.34)\\
&+ (MM\Psi_{z_1} + \Psi(\ )\ )dz_1 + (\alpha f_{L_E} + z_1)dL - dz_2 = 0
\end{aligned}$$

By reorganizing this into matrix form, it can be expressed in a compact form:

$$\begin{bmatrix} j_{1\eta} & j_{1\lambda} & j_{1W} & 0 \\ 0 & r & 0 & \varrho R_{SS} \\ G_N\Phi_\eta & G_N\Phi_\lambda & (G_N\Phi_W - \varphi) & 0 \\ MM\Psi_\eta & MM\Psi_\lambda & MM\Psi_W & 0 \end{bmatrix} \begin{bmatrix} d\eta \\ d\lambda \\ dW \\ dS \end{bmatrix} = \qquad (1.35)$$

$$\begin{bmatrix} q_{1\alpha} & q_{1z_1} & -\eta & -\eta & q_{1\bar{L}} & 0 & 0 \\ 0 & 0 & -\lambda & 0 & 0 & -R_S & 0 \\ -G_N\Phi_\alpha & -G_N\Phi_{z_1} & 0 & W & 0 & 0 & 0 \\ q_{4\alpha} & q_{4z_1} & 0 & 0 & q_{4\bar{L}} & 0 & 1 \end{bmatrix} \begin{bmatrix} d\alpha \\ dz_1 \\ dr \\ d\varphi \\ d\bar{L} \\ d\varrho \\ dz_2 \end{bmatrix}, \qquad (1.36)$$

where $j_{ix}$, $q_{iy}$ and MM are written out below:

$$\begin{aligned}
MM &= (z_1 - \alpha f_{L_E}) < 0 \\
q_{4\bar{L}} &= (z_1 + \alpha f_{L_E}) > 0 \\
j_{1\eta} &= (r + \varphi) - \Lambda_W[U_C C_E E_{L_E} L_{EL}\Psi_\eta + U_C C_N \Phi_\eta + U_L\Psi_\eta] >< 0 \\
j_{1\lambda} &= -\Lambda_W[U_C C_E E_{L_E} L_{EL}\Psi_\lambda + U_C C_N\Phi_\lambda + U_L\Psi_\lambda] >< 0 \\
j_{1W} &= -\Lambda_{WW}U(\ ) - \Lambda_W[U_C C_E E_{L_E} L_{EL}\Psi_W + U_C C_N\Phi_W + U_L\Psi_W] >< 0 \\
q_{1\alpha} &= \Lambda_W[(U_L + U_C C_E E_{L_E} L_{EL})\Psi_\alpha + U_C C_N\Phi_\alpha] \\
q_{1z_1} &= \Lambda_W[(U_L + U_C C_E E_{L_E} L_{EL})\Psi_{z_1} + U_C C_N\Phi_{z_1}] \\
q_{1\bar{L}} &= \Lambda_W U_C C_E E_{L_E} L_{E\bar{L}} < 0 \\
q_{4\alpha} &= (z_1 - \alpha f_{L_E})\Psi_\alpha + f(\bar{L} - \Psi(\ )\ ) \\
q_{4z_1} &= (z_1 - \alpha f_{L_E})\Psi_{z_1} + \Psi(\ )
\end{aligned}$$

The partly signed matrix, $\mathcal{J}$, appears as

$$\mathcal{J}' = \begin{vmatrix} ? & ? & ? & 0 \\ 0 & (+) & 0 & (+) \\ (+) & (-) & ? & 0 \\ (-) & (+) & ? & 0 \end{vmatrix} \tag{1.37}$$

While most of the elements can be signed, there are five of them which are left ambiguous. To find the determinant $|\mathcal{J}|$, the matrix is expanded on the last column. According to Dockner (1985), for the local saddlepoint stability it must hold that $|\mathcal{J}| > 0$, and that $K$, a sum of three determinants of $\mathcal{J}$'s submatrices, is negative, where

$$K = \begin{vmatrix} j_{33} & j_{31} \\ j_{13} & j_{11} \end{vmatrix} + \begin{vmatrix} j_{44} & j_{42} \\ j_{24} & j_{22} \end{vmatrix} + 2 * \begin{vmatrix} j_{34} & j_{32} \\ j_{14} & j_{12} \end{vmatrix} < 0. \tag{1.38}$$

This tells us that $|\mathcal{J}|$ is positive if $j_{11}$ and $j_{12}$ are negative, $j_{13}, j_{33}$ and $j_{43}$ are positive, and that $(j_{31}j_{42} - j_{41}j_{32}) > 0$.

Many of these conditions for the existence of a local saddlepoint steady state have an intuitive meaning. The condition $j_{43} > 0$ is equivalent to $L_W < 0$. This means that when the nuclear waste stock grows, less land is allocated in food production, which in turn means that more land is allocated in energy production. Intuitively this means that energy production diverts more land towards biomass energy as the nuclear waste stock increases.

The condition $j_{33} > 0$ boils down to a requirement the $N_W > 0$. This means that when the nuclear waste stock increases, the use of nuclear power is increased. Such a result sounds somewhat peculiar. However, this may result from the type of equation of motion in our model. According to the chosen model, the large waste stock decreases the increment in the stock through the decay coefficient. In practice, the effect is very small and thus not very significant.

The last condition $(j_{31}j_{42} - j_{41}j_{32}) > 0$ can be reduced to $L_\lambda/L_\eta < N_\lambda/N_\eta$. This means that (negative) value of carbon dioxide stock affects land use relatively more than (negative) value of nuclear waste stock, and vice versa. Noting that $\eta$ affects both variables positively and $\lambda$ negatively, it can be concluded that the changes in the "own" stocks are not as strong as the changes in "other" stock. The other three conditions do not have quite as clear an economic interpretation. Next, the system is further characterized by doing sensitivity analyses.

## 1.6 Comparative Statics and Envelope Results

In this section the short run comparative static (SRCS) results are reported, which were determined as part of stability analysis. After that the steady state omparative statics results (SSCS) and dynamic envelope results are determined and reported. Above, the stability conditions were evaluated in order to determine the general conditions which are required for a stable steady state solution to exist. In this way it could shown that it actually is possible to find a situation where it makes sense to devote some of the agricultural land to energy production. The analysis shows the general conditions which must be fulfilled for such a situation to occur. After showing that such a situation is possible, a natural next step is to evaluate the nature of the steady state. This further characterizes the conditions by showing how changes in some key parameters will affect the system. In numerical analysis this is called a sensitivity analysis, as it suggests the magnitude of the effects of the parameter changes on the system, however, in a theoretical analysis one is interested in the direction of the changes.

In the present case, I focus on the most interesting parameters in the system, which are $\varrho$, $\alpha$, $z_2$, $r$ and $L$. The first one, $\varrho$, signifies the damage due to the accumulation of carbon dioxide. Comparative static analysis with respect to this parameter shows what happens to the states, to the co-states and to control variables when damage from the carbon dioxide stock increases. The parameter $\alpha$ describes carbon effluents from biomass energy production. Even if one assumes the biological and chemical relationships remain the same in energy feedstock growing, it is probable that in the future the processing, transportation, and utilization develops to be more and more efficient. The effects of such a situtation can be seen through the comparative static results with respect to the $\alpha$ parameter. The effects of the assimilation capacity of other sources (e.g., forests and seas) can be seen by evaluation of $z_2$. Eventually the effects of the changes in discount rate and total agricultural land area are evaluated by adjusting $r$ and $\bar{L}$, respectively.

### 1.6.1 The Short Run Comparative Static Results

The short run (or instanteaneous) comparative static results, were presented above in the equations (1.20) - (1.25). The SRCS's are simply the effects of changes in the parameters on the states and the co-states. They are partial responses to a change in one variable or parameter, when everything else is held constant. This means that the other states and co-states are not allowed to adjust to changes in the parameters. These parameter changes were already evaluated above for the purpose of stability analysis and thus one may look at the results from there.

The results of SRCS are reported in the third group of equations in the previous section (1.20) - (1.25). The effects of increasing the size of radioactive stock is left ambiguous with respective to both the control variables. However, as a condition for the stability to exist it is required that $L_W < 0$ and $N_W > 0$. These stability conditions are intuitively clear as discussed in the end of the previous section. The decrease of the cost (or shadow value) of the carbon stock has a negative effect on both the food agreage and nuclear power usage. The effect on energy crop acreage is positive. An increase in units of carbon effluents for biomass energy increases food acreage and nuclear power usage, but decreases the energy crop acreage. Similarly an increase in the carbon assimilation capability increases energy crop acreage and decreases both food acreage and nuclear power usage. The decrease of the cost (or shadow value) of the radioactive waste stock has a positive effect on the food acreage and nuclear power usage and a negative effect on energy crop acreage. The effect of the increment of total land resources are left ambiguous. The reason for the last point is that it is not clear for which purpose the extra land would be used.

### 1.6.2 The Steady State Comparative Static Results

The steady state comparative statics (SSCS) results are evaluated for the parameters $r, \varrho, \bar{L}, \varphi$ and $z_2$. The SSCS can be evaluated from the system $\mathcal{J}x = \mathcal{Q}y$ above using Cramer's rule. In signing the results the stability conditions determined in the previous section are utilized. The results are as follows:

$$d\eta/dr < 0, \quad d\lambda/dr < 0, \quad dW/dr > 0, \quad dS/dr >< 0, \tag{1.39}$$

$$d\eta/d\varphi >< 0, \quad d\lambda/d\varphi >< 0, \quad dW/d\varphi > 0, \quad dS/d\varphi >< 0, \tag{1.40}$$

$$d\eta/d\bar{L} >< 0, \quad d\lambda/d\bar{L} > 0, \quad dW/d\bar{L} >< 0, \quad dS/d\bar{L} < 0, \tag{1.41}$$

$$d\eta/d\varrho = 0, \quad d\lambda/d\varrho = 0, \quad dW/d\varrho = 0, \quad dS/d\varrho < 0, \tag{1.42}$$

$$d\eta/dz_2 >< 0, \quad d\lambda/dz_2 > 0, \quad dW/dz_2 > 0, \quad dS/dz_2 < 0, \tag{1.43}$$

The comparative static effects for $\alpha$ and $z_1$ could not have been determined. According to the results the discount rate affects the shadow prices of both stocks inversely whereas the effect on nuclear waste stock is positive and that on the carbon dioxide stock is ambiguous. In practise, this means that when future utility is more heavily discounted the cost of pollution is lower. This creates an incentive to hold larger stocks. A change in the decay rate of radioactive waste stock is left ambiguous except for the nuclear waste stock. For larger decay rates a larger nuclear waste stock is held. A change in the total land area affects the carbon stock size inversely, whereas its shadow value is affected positively. The effects on radioactive waste stock and its shadow value are ambiguous.

The parameter $\varrho$, a scaling parameter for carbon based disutility, reflects a vulnerability of different countries and regions: the same size carbon stock may cause more damage in country $A$ than in country $B$. This scaling parameter inversely affects the carbon stock level. This implies that if a country becomes more vulnerable to climate change problems in the steady state situation, the carbon dioxide stock should be adjusted downwards. For instance, for a flat highly populated region with possibility of flooding, a careful carbon management is very important. All other effects from changes in the scaling parameter are zero. The parameter $z_2$, which measures exogeneous carbon absorbtion, has a positive effect on the radioactive waste stock as well as on the carbon stock shadow value. The effect on carbon stock itself is negative, whereas an effect on the nuclear waste stock shadow value is ambiguous. Intuitively this says that if exogeneous carbon absorbtion is increased (e.g., through forestation or accelerated photosynthesis in the seas) the carbon stock level decreases.

The steady state comparative static results on control variables are found using the equations (1.26) - (1.27) above, now written as functions of optimal states and co-states as follows:

$$L = \Psi(W^*(\beta), \lambda^*(\beta), \eta^*(\beta); \alpha, z_1) \tag{1.44}$$

$$N = \Phi(W^*(\beta), \lambda^*(\beta), \eta^*(\beta); \alpha, z_1), \tag{1.45}$$

where $\beta = (\varrho, \alpha, z_1, z_2, r, \varphi, \bar{L})$. By differentiating above functions with respect to parameter values, we found the comparative static effects on control variables. These are then evaluated utilizing the results from the equations (1.20) - (1.25) and (1.40) - (1.44).

Most of these results are ambiguous, however, it can be determined, that $dL^*/d\varrho = 0$, and similarly $dN^*/d\varrho = 0$. This simply means, that in the steady state, changes in regions' vulnerability to climate change does not affect the optimal control levels, although it affects the optimal steady state carbon stock. In the following section the dynamic envelope results are evaluated.

### 1.6.3 The Dynamic Envelope Results

For the dynamic envelope results, one can follow the dynamic envelope theorem of Caputo (1990, 1995, pp.250). In principle, it is a four-step program: 1) form the Hamiltonian for the problem, 2) differentiate the Hamiltonian with respect to parameter(s) of interest, 3) substitute in the optimal paths of the state, co-state and control variables and 4) integrate the results. For this problem the results are as follows:

$$\mathcal{J}^*_\varrho(\beta) = -\int_0^\infty R(S^*(t;\ \beta))e^{-rt}dt < 0 \tag{1.46}$$

$$\mathcal{J}^*_\alpha(\beta) = \int_0^\infty \lambda^*(t;\ \beta)f(\bar{L} - L^*(t;\ \beta))e^{-rt}dt < 0 \tag{1.47}$$

$$\mathcal{J}^*_{z_1}(\beta) = -\int_0^\infty \lambda^*(t;\ \beta)[\bar{L} - L^*(t;\ \beta)]e^{-rt}dt > 0 \tag{1.48}$$

$$\mathcal{J}^*_{z_2}(\beta) = -\int_0^\infty \lambda^*(t;\ \beta)e^{-rt}dt > 0 \tag{1.49}$$

$$\mathcal{J}^*_\varphi(\beta) = -\int_0^\infty \eta^*(t;\ \beta)W^*(t;\ \beta)e^{-rt}dt > 0 \tag{1.50}$$

$$\mathcal{J}^*_{\bar{L}}(\beta) = \int_0^\infty \Lambda(W^*(t;\ \beta))U_C E_{L_E}(\bar{L} - L^*(t;\ \beta)) \tag{1.51}$$

$$+ \lambda^*(t;\ \beta)(\alpha f'(\bar{L} - L^*(t;\ \beta)) - z_1)]e^{-rt}dt >< 0 \tag{1.52}$$

Here $J^*(\beta)$ is the present value optimal value function for the control problem (i.e., the societal dynamic indirect utility function.). These results are called dynamic envelope results and show how (little) changes in the system's parameters affect the optimal value function in the control problem.

In words, the first equation means that whether disutility from carbon stock is scaled upwards, the present discounted value of utility decreases. In the second equation, it is shown that a decrease in the effluent per unit of biomass energy used (for example by adopting some new technology) increases the present discounted value of utility. The following equation states that increased amount of carbon absorbtion for biomass energy production (e.g. through better cultivation methods) increases the present discounted value of utility. An increase in the exogeneous carbon absorbtion causes a similar effect. The result for $\varphi$ shows the effect of a change in the nuclear waste decay rate: if one was able to increase the decay rate, the present discounted value of utility would increase. In the last equation, the effect of the change in total land area is the only one left ambiguous. This is due to the fact that the effect depends on how this additional land area would be utilized, either in food or in biomass energy production.

## 1.7 Summary and Conclusions

In this paper a problem of energy production and land allocation was investigated. The study was prompted by the recent debate about the appropriate energy production method in Finland. The problem was set up such that a society receives utility from energy consumption and food consumption. In the model the energy needs are fulfilled either by nuclear power or by biomass energy. As biomass energy and food are both produced on agricultural land they compete for the same resource. The main question is, how to divide the agricultural land for alternative uses and how much nuclear power to produce. In the analysis, the conditions were determined which provide necessary and sufficient conditions for the local saddlepoint stability of the steady state for this program. After that, short-run and steady state comparative statics results and dynamic envelope results were reported.

In proving the stability of the steady state the Dockner's approach was used, which naturally lends itself for comparative static analysis. The comparative statics effects on control variables due to changes in parameters and states and co-states were valued in the process of proving the stability. In the short run comparative static analysis states and co-states were treated as parameters. The results were intuitive, except the stability result, that an increment in nuclear waste stock should increase a use of nuclear power. This seems to be driven by the natural decay of waste, and is thus very small in size and insignificant for policy purposes. Next, in the steady state comparative static analysis the effects of parameter changes on the states, co-states and controls were evaluated. Eventually, the so-called dynamic envelope results were found. The results from these analysis were all plausible and followed economic intuition.

The problem analyzed here has a lot of contemporary interest when a choice of "right" energy sources is again debated. Whereas in the sixties the issue of resource scarcity was an important concern, nowadays a general theme seems to be waste utilization and waste management. It is the management of the quality of the environment that matters, rather than the management of the physical resource base. This study is an addition to the energy and pollution literature since two different type of externalities are modeled jointly; namely a possibility of a catastrophic event and a slowly increasing nuisance stock. As a generalization this approach is new. Similar cases have earlier been evaluated only in some empirical programming studies.

In future work, the model can be extended by adding in international common property issues such as transboundary pollution. In the most simple form this could be done by adding in another country in the manner of Negri (1989). In such a model the difference between the two pollutants could be emphasized by assigning the radioactivite waste to be a "local" pollutant harming only inhabitants in the country of its origin. In contrast, $CO_2$ spreads around in a nondiscriminatory manner harming the whole world more evenly. Another interesting extension comes from trade literature: how does the possibility of trading either energy (e.g. electricity) or waste products change the results of this basic model? Still another interesting question is increasing food demand and land pressures due to population growth.

As a first part of the dissertation, this essay sets a base for a further analysis. Here it was proven, with a very general theoretical model, that biomass energy could be used as one energy type in society when pollution evokes some concern. A clear land pressure between food production and energy biomass feedstock has also been demonstrated. In the following chapter the concern is, how to manage biomass stock on a micro level as an asset management problem. After that, general farm level production problematics are evaluated in a practical manner.

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# Essay 2

# Recursive Preferences in Forest Management

Expected Net Present Value is a commonly used criterion for determining optimal management schedules for stochastically growing forest stands. However, this method only applies to a case where the owner is risk neutral. If the owner has other risk preferences, the modeling should be done using a utility function. The expected utility (EU) approach is the most common way to handle stochasticity in an atemporal framework, although there are some theoretical concerns in using EU. In intertemporal problems EU is even more problematic as it does not reveal the behavioral motivation behind a chosen optimum, namely it cannot distinguish between the effects of time preference and risk attitudes.

Non-Expected Utility, or more specifically, Recursive Preferences are a reasonably recent development. The Recursive Preferences approach is able to disentangle risk-aversion and intertemporal substitution effects when measuring utility in a dynamic setting and, thus, using this approach the aforementioned problems can be overcome. In this paper, Recursive Preferences are applied to forest management. Using this framework, the relative importance of reasons behind specific management schedules, namely risk aversion and intertemporal substitution, can be weighed. In that way, the new measure produces additional valuable information. Additionally, as EU is a special case of the Non-Expected Utility formulation, the outcomes from these models can be easily compared. The approach has been used in macroeconomic literature during the past ten years, but it was only recently applied to micro level resource problems.

## 2.1 Introduction

This study addresses the problem of optimal harvests in a forest stand in a decision environment plagued by stochasticities. In non-stochastic forestry studies, net present value (NPV) concept is commonly used as the objective function. When non-pecuniary benefits are included, a behavioral model must be used. A Fisherian two-period model is used in an intertemporal cost-savings framework and in several tax scheme studies both in deterministic and stochastic settings. Often in stochastic studies, in order to keep the problem tractable, risk neutrality is assumed. Generally, risk enters through growth or price functions, however, there are examples where risk is assumed to enter as a form of a catastrophe, such as wildfire or insect attacks.

The expected net present value (ENPV) concept applies to a case of risk-neutrality, but in the case of a risk averse forest manager, production and consumption decisions cannot be separated and the approach cannot be used. In a static framework a natural extension in this case would be an expected utility (EU) measure. However, there seems to be very few studies with EU where risk-aversion is incorporated. Besides several tax studies utilizing the two-period model, our brief survey of the forestry literature revealed only a few rotation analyses that include risk aversion (see Caulfield, 1988; Taylor and Fortson, 1991; Taylor, 1989). Besides forestry there are a few other examples of dynamic, stochastic, risk non-neutral modeling e.g. a study by Karp and Pope (1984) on range management.

Due to both, theoretical and empirical concerns, EU approach seems unsuitable and unappealing in an intertemporal setting. The main theoretical criticism against the EU approach is that it violates the von Neuman-Morgenstern independence axiom, one axiom its existence relies on. Another bothersome point is its indifference of the timing of uncertainty resolution. From an empirical point of view, the approach is handicapped as it cannot distinguish between the roles of time preference and risk attitudes in the agent's decision making (Epstein, 1992; Zacharias, 1993).

This study uses a recursive preference (RP) formulation to study optimal forest harvesting. The RP approach is a reasonably recent development. In the theoretical literature, a deterministic version of the RP approach was borne in the sixties (Koopmans, 1960 and 1964) and it was extended to the stochastic case by Kreps and Porteus in the next decade (1978, 1979a, 1979b). An empirically interesting version emerged only less than ten years ago, when Epstein and Zin (1989) and Weil (1990) simultaneously parameterized the notion. So far the approach has been mainly popularized in the econometric macroeconomic literature. This study is one of the first applications to a micro level resource problem, although an exploration of this kind of approach in resource studies was suggested ten years ago by Zacharias (1993). There are only two pioneering studies by Knapp and Olson (1996a, 1996b) and a recent paper by Koskela and Ollikainen (1998) and another by Epaulard and Pommeret (1998). The studies by Knapp and Olson are especially interesting as mathematical simulations are utilized for the first time in connection with RP.

The optimization of forest harvesting is a very important application as observed annual levels of harvest and marketed wood vary, and thus also annual growth and forest biomass levels fluctuate over the years. Some of the variation clearly results from demand changes, however, some of the variation is left unexplained. Private forest owners actions may be followed and registered, but so far the motives behind the action have been difficult to recover. Especially, it has been difficult to separate the effects of risk aversion and intertemporal elasticity of substitution (IES). In turn, when motives behind certain actions are not known the remedies for these motives cannot be designed either. For instance, forest owners may keep apparently inefficiently large growing forest stock and are reluctant to sell enough (=seemingly economically optimal) amount of wood annually. If the reason for such a behavior is high risk aversion, e.g. altering capital markets does not help. Instead, the motive behind the actions have to be found, only then may necessary measures be taken.

Our model looks at a forest stand from a capital asset management perspective in an infinite time horizon, and determines the optimal harvesting time according to biological and economic factors. The main goal is to determine an economically efficient harvesting rule based on a particular type of Non-expected Utility (NEU) function, rather than EU or ENPV. Specifically, we introduce a Recursive Preference approach into traditional stochastic forest rotation models. From an empirical point of view this modeling approach is interesting as it accounts for owner's time preference and risk attitudes separately. It deals with two issues: 1) how to manage a biological asset under stochastic conditions, and 2) how these management decisions are affected by time preference and risk attitudes. Besides forestry problems, this approach naturally applies to several other stochastic dynamic problems, e.g., fisheries, use of water resources and range management, etc.

In summation, in this study: *i) the Recursive Preferences formulation to micro level resource management modeling is introduced, ii) the optimal harvest schedule is found using a mathematical simulation, and iii) a practical significance of such a modeling approach is evaluated by comparing the results to those from traditional ENPV-formulation.* First, we examine different types of forest rotation studies. Then, we briefly discuss the concerns and difficulties associated with the EU measure in an intertemporal setting and review the alternative based on recursive preferences. In the next stage, the model and data simulation procedure are presented. Then we compute the optimal management schedule using the RP approach utilizing two alternative functional specification and compare the results with those from a base case ENPV analysis. Finally, the significance of the results is discussed.

## 2.2 Traditional Forestry Modeling

Finding an optimal forest rotation has been a keen interest of researchers for at least a century judging from the size of the literature on this topic. A German forester, Faustmann, seems to have found the basic solution to the question in the middle of the last century, given strict conditions for information, growth and price levels. However, discussion over the correct formulation has continued since. This section reviews the forestry literature, beginning with deterministic models and then considering stochastic models.

Foresters often suggest a rule that guarantees maximum sustainable yield (MSY) from a given acreage. The MSY rule is based on biological facts only and, thus, does not take into account impatience nor alternative investment possibilities. A common suggestion by economists is to account for these factors resulting in a so called wine-aging solution. The resulting cutting rule normally suggests cutting forest before it reaches the level of MSY. According to Faustmann's still more general rule, the forest owner must also account for the rent available from the land area. This results in still shorter cutting times. Good reviews of forest rotation rules can be found in Johansson and Löfgren (1985), Reed (1986), Newman (1987) and Löfgren (1990).

Faustmann's forestry rotation rule from 1849 (Faustmann, 1995) has eventually been accepted as the proper rule for forest management by the main body of economists and foresters alike. However, Faustmann's analysis rests on several very restrictive assumptions, which Reed (1986) lists as follows: 1) known future prices and costs of lumber; 2) known future interest rates; 3) known future biological growth characters; 4) perfect land markets; 5) instant harvest; 6) no externalities; 7) no catastrophies; and 8) perfect, unrestricted capital markets. Although the assumptions are restrictive as such, they help to produce a clear answer to a simplified problem.

The early forestry papers mainly follow the lead of Faustmann. They use a similar deterministic modeling approach, maximize NPV, and use calculus to find an optimal time for cutting. With the development of new modeling and solution methods, several extensions have been introduced. In the sixties, researchers studied the same basic problem using the same deterministic framework but added in thinning possibilities and utilized new solution methods. The well known thinning model is due to Kilkki and Väisänen (1969), where they use dynamic programming to evaluate optimal thinning times. Näslund (1969) provides an analytical optimal control formulation, where Pontryagin's maximum principle is used. Later, Clark and De Pree (1979), Cawrse et al. (1984), and Steinkamp and Betters (1991) used variational methods to find an optimal program for a forest owner. All of these studies maximize NPV in a deterministic setting. Heaps (1981) investigated qualitative properties of the rotation and provided an extensive comparative static results for this case. In another paper, Heaps and Neher (1979) studied the question in a more general framework, and Heaps (1984) introduced a so called generalized forestry management problem using a Pontryagin type of approach.

In addition to these general rotation studies, there are several others where other benefits besides wood market value are included. Hartman (1976) generalized the Faustman model to include amenities such as recreation benefits. Hartman's model was further extended by Strang (1984). Other extensions of rotation analysis are spatial issues with a single forest stand by Swallow and Wear (1993), climate change issues by van Kooten et al. (1995) and Tahvonen (1993), special growth patterns (coppicing species) by Medema and Lyon (1985) and Tait (1987). Medema and Lyon (1985) use a traditional calculus method, whereas Tait (1987) proceeds with dynamic programming recognizing a simple recursive relationship in the program. Besides the studies mentioned above, which are concerned with the correct economic approach, there are several others that emphasize the efficiency of the calculation process itself. In these papers alternative solution methods and computing algorithms for rotation optimizations are evaluated (see Valsta, 1990 and 1992b; Roise, 1986a and 1986b).

A fresh approach using a utility function is by Max and Lehman (1988), following a lead by Binkley (1981), where they model timber supply decisions with a behavioral model. In the model, a forest owner attains utility from consumption as well as forest recreation/amenities. For a similar type of modeling procedure, see e.g. Johansson and Löfgren (1985) and Boyd (1983), where a traditional Fisherian two-period model is used by adding the growth function of trees to an inter-temporal cost-savings setting. This model can be used to analyze a timing of the cuttings and timber supply in the short run. Koskela (1989a and 1989b) and Ollikainen (1990) and Koskela and Ollikainen (1995 and 1996) have used this same framework in several studies both in a deterministic and stochastic framework to analyze the effects of alternative tax schemes on wood supply in Finland.

Recently there has also appeared two studies using an overlapping generations (OLG) approach to model forestry management decisions, in cases when there are two differing owner groups, e.g. "young" and "old". Such a division allows analysis concerning special behavior due to the group characteristics. Löfgren (1991) and Hultkranz (1992) use an OLG modeling to include a bequest motive in order to theoretically explain empirical regularities left unexplained by traditional rotation models. In these OLG studies, utility functions include broad range of preferences besides simple money income, but commonly the set-up is always deterministic.

One of the Faustmann assumptions was that a manager has full deterministic information about tree growth as well as price and market developments. This is clearly not realistic. In practice, forestry production is a long-run process containing lots of uncertainty and, therefore, for proper modeling, we need to include stochasticity. Analyses incorporating stochasticity have already been done, however, normally by using a convenient assumption about the manager's risk neutrality and invoking Fisherian separation theorem. This lets one use ENPV models and concentrate on the production side alone. If risk averse behavior is allowed, and risk (or finance) markets are not perfect, the Fisherian separation theorem is violated and production and consumption decisions must be modeled jointly. Therefore, a utility function instead of ENPV as an objective function has to be used. However, risk aversion is not considered in most studies.

The studies in which the management problem includes stochasticity either due to stochastic prices and/or growth, are closely related to the research at hand. Hool (1966), Lembersky and Johnson (1975), and Lembersky (1976) are pioneering probabilistic studies utilizing probability transition matrices. Studies by Kao (1982 and 1984) popularize a usage of dynamic programming with a probabilistic growth function. Miller and Voltaire (1983) and Clarke and Reed (1989 and 1990) use Ito calculus to analyse the problem. A similar approach is taken in Reed (1993), where management is an optimal stopping problem with an irreversible decision. In all of these studies, risk neutrality is assumed and therefore the resource management issues can be modeled independent of consumption decisions (See also Yin and Newman 1995). Consistent findings are that increasing risk in the form of catastrophe shortens the optimum rotation considerably (Martell, 1980; Routledge, 1980; Reed and Errico, 1985; Caulfield, 1988). The stochasticites due to uncertain price and growth patterns have been not been found to affect an optimal forest rotation as significantly (Lohmander, 1987; Brazee and Mendelsohn, 1988).

In more specific studies, Kaya and Buongiorno (1987) evaluate the effects of growth and price risk in uneven-aged forest stand management. Brazee and Mendelsohn (1988) design a flexible harvest schedule for a forest owner in the case of fluctuating prices, thereby launching the idea of a reservation price. Forboseh et al. (1996) use a similar reservation price scheme to evaluate management strategy for a multiproduct stand. Teeter and Caulfield (1991) also look at the price uncertainty effect on density management and find it somewhat significant in thinning decisions, whereas they suggest it not to be very important in final harvesting decisions. A somewhat different study is by Haight and Holmes (1991), which analyse stationarity versus non-stationarity issues in wood prices and the effects of these on rotation optimization.

Van Kooten et.al (1992) present an interesting analysis of uncertain timber growth using a large scale simulation model. Uncertainty comes as a form of uncertainty on the effect of management actions. Valsta (1992a) also uses a large set of scenarios, each of which is an outcome of stochastic processes in a very detailed study using a single-tree growth and mortality models. In both studies, a risk-neutral manager is assumed and thus an ENPV criterion can be utilized in the optimization.

Our survey of forestry literature yielded only a couple of rotation analyses including risk aversion, besides the several studies by Koskela and Ollikainen using a two-period model. Caulfield (1988) models a management scheme for a forest which is subject to a catastrophic hazard (wildfire) and for which the owner is risk averse. His model is based on the model by Martell (1980) and applied to a Loblolly Pine stand. The author modifies Martell's model such that first and second degree stochastic-dominance methods can be utilized as a decision making tool. However, stochastic dominance criteria appears problematic as it may result in a set of several "optimal" strategies and thus the truly best one cannot be extracted. Of course in some cases this could also be seen as beneficial: the analysis can be used as a preliminary screening method, which leaves room for a decision maker to exercise her own, maybe broader, management preferences.

Also allowing risk aversion, Taylor and Fortson (1991) and Taylor (1989) build a simulation model for Loblolly Pine accounting for price, survival and yield risks. The authors use a simulation method launched by Hertz (1964). The technique is based on a Monte Carlo simulation utilizing probability distributions for some variables as means of introducing variation into the calculation of project return. Measurement of the extent of return deviation constitutes the degree of risk. Taylor and Fortson apply this technique in their study, however, using a very simple utility function. The function appears static by its very nature and does not seem to fit naturally into dynamic analysis, where an agent may be forward looking. Also, nothing can be said about the motives behind a manager's actions, for instance, what the role of intertemporal substitution is.

Besides forestry, there are some examples of dynamic, stochastic, risk non-neutral modeling in other resource management contexts. For instance Karp and Pope (1984) model range management decisions under stochastic conditions and with risk-neutral, -loving and -averse owners. In the study, the agents maximize expectectation of the discounted sum of the utility from profits at each period. All in all, it seems that not many dynamic resource management studies allowing risk aversion exist. As this may be partly due to a lack of suitable methodology, it is important that new potential approaches are reviewed and tested.

## 2.3 Non-Expected Utility Formulation and Recursive Preferences

The surveys of Caulfield (1988) and Zacharias (1993) as well as our own brief survey suggest that there exist very few articles modeling stochastic resource problems with risk aversion. The scarcity of dynamic risk-aversion studies seem to suggest that a suitable modeling approach for such problems is still missing. The particular reason for the present study is to evaluate one possible alternative in forestry management context.

Static expected utility (EU) modeling has been mainly criticized due to its reliance on the so called independence axiom (Machina (1987, 1989), Quiggin (1993), Epstein (1992). Albeit this criticism, the EU modeling has become the main venue for stochastic atemporal problems. In an intertemporal framework Zacharias (1993) notes two theoretical problems, first, the similar reliance (and possible violations) of the von Neuman-Morgenstern independence axiom. The second problem is agents' indifference on the timing of resolution of uncertainty due to the construction of the utility function. Intuitively, agents could be thought to prefer an earlier resolution of uncertainty to that of later as that allows one to plan consumption better (see Epstein and Zin 1989). The incapability of expected utility modeling in separating intertemporal substitution issues from risk aversion were pointed out by Mossin (1969) and Spence and Zeckhauser (1972). In the same vein, Weil (1990) emphasizes general theoretical difficulties when attempting to separate risk aversion and intertemporal substitution from each other, as often either the stationarity assumption or time consistency of preferences is violated.

Empirically the problem is that in an EU model risk aversion and intertemporal substitution are reciprocals of each other, i.e. high risk aversion implies low intertemporal subsitution and vice versa. The effects of intertemporal substitution and risk aversion cannot be separated as they enter in through the same parameter. This imposes a rigid structure to a program and thus does not allow one to search for motives underlying agent's action. Thus, besides the above theoretical concerns, expected utility modeling is clearly handicapped from a practical point of view.

### 2.3.1 Theoretical Development

Due to the aforementioned problems, generalizations to standard expected utility modeling have been sought. Selden (1978) extended a two-period expected utility model constructing a two-part two-period utility function, where the first part is a deterministic current consumption and the second part is a certainty equivalence of uncertain second period consumption. This so called OCE (ordinal certainty equivalent) model is based on conditional second-period expected utility and on a two-period ordinal index. Another suggestion for a generalization is a *Recursive Preference* (RP) approach, the approach used in this study. It is one example of *Non-Expected Utility* (NEU) models. The RP approach is preferable as it does not rely on the independence axiom. Furthermore, it allows one to separate the effects of risk aversion and intertemporal subsitution, and is thus empirically more desirable.

Koopmans (1960) introduced recursive utility functions in a deterministic setting. The author showed that somewhat elementary properties of a utility function (continuity, stationarity, sensitivity, existence of the best and worst programs and absence of intertemporal complementarity) can imply an existence of *impatience* in a preference structure i.e., a preference for advancing the timing of future satisfaction. Basically this means that if $U(x) \succ U(x')$ for any given year, then $U(x_t, x'_{t+1}, ...) \succ U(x'_t, x_{t+1}, ...)$ i.e., a consumer's utility is increased by having a more desirable bundle sooner.

In a subsequent paper Koopmans et.al. (1964) clarified a deeper property called *time perspective.* This property extends the impatience concept by saying that given $(x'_t, x''_{t+1}, x'''_{t+2}, ...) \succ (y'_t, y''_{t+1}, y'''_{t+2}, ...)$, the difference between the programs shrinks, if their appearance is postponed. Mathematically this can be written as follows: $(z_t, z_{t+1}, x'_{t+2}, x''_{t+3}, ...) \succ (z_t, z_{t+1}, y'_{t+2}, y''_{t+3}, ...)$, where a difference between the two latter problems is smaller than that of the original programs. The main structure resulting from Koopmans work was a a system of calculating present utility as a function of current consumption and future utility. An aggregator function, $W$, is used to combine these two different elements as follows:

$$V(c_0, c_1, c_2, ....) = W[c_0, V(c_1, c_2, ....)]. \tag{2.1}$$

Furthermore, in defining impatience Koopmans was originally able to use ordinal utility functions whereas in the latter paper the authors had to resort to a so-called quasi-cardinal utility presentation. A second major constraint is that the possibility of habit formation and time-wise consumption complementary in agents' preferences are ruled out. The work on this deterministic recursive preferences has continued especially in growth models in general equilibrium framework. An interested reader may consult a recent survey by Becker and Boyd III (1993) and an article by Dolmas (1996).

As a next step, following directly Koopmans' lead, Kreps and Porteus (1978a, 1978b; 1979) extend the deterministic recursive approach to cover stochastic problems resulting in the following expression of utility:

$$U_t = W[\pi_t, \mu_t(\tilde{U}_{t+1})], \tag{2.2}$$

where $\pi$ is profit, $\mu_t$ is a transformation function for expected future utility and $W$ is an aggregation or transformation function for current profits and future expected utility.

From a practical point of view, another major step forward was a paper by Epstein and Zin (1989), who constructed a general class of preferences free of the problems normally linked to EU approach. The generalization includes as subsets 1) EU preferences with an intertemporally additive and homogeneous von Neuman-Morgenstern utility index, 2) infinite-horizon extension of Kreps-Porteus structure and 3) as a further generalization embedding atemporal non-expected utility theory by Chew (1989) and Dekel (1986).

As a definitional detail, a utility function is called recursive if it satisfies the following equation in its domain:

$$V(c_0, c_1, c_2, ...) = W[c_0, \mu(V(c_1, c_2, ...))], \tag{2.3}$$

for some increasing $W$ and some certainty equivalent $\mu$. This recursive structure implies *a) intertemporal consistency*[1], which means, loosely speaking, that if a consumer chooses a certain consumption plan now, she does not want to change it later, i.e.

[1] According to Johnsen and Donaldson (1985) time consistency implies that if a decision maker is able to anticipate and plan against any future contingency at time $t_0$ and she chooses $R_0$, then this plan will also be optimal in future stages. This is somewhat analogous to the concept of *subgame perfect* in game theory. In other words, after a person chooses a consumption path at time $t = 0$, knowing potential future stochastic outcomes, if she then follows this path in the next period(s), we can conclude that her preferences are time constant, otherwise we must conclude that there was a change in taste. This is called Time Consistent Planning (TCP). This approach does allow for a habit formation, but it does not allow for a so called regret. The authors further point out that a customary expected utility representation is not needed for time consistent planning. Subsequently the authors create a tree structure of preferences which is time consistent. This counters the time consistency of Weller (and Hammond), which suggest that intertemporal consistency is equivalent of maximizing expected utility (cited by Johnsen and Donaldson (1985). Also citing Johnsen and Donaldson, Epstein (1992, pp 19), emphasizes further that constant tastes ensure dynamic consistency. Mathematically the idea is written as follows: Having programs $\tilde{c} = (\tilde{c}_0, \tilde{c}_1, \tilde{c}_2, ..., \tilde{c}_T, \tilde{c}_{T+1}, ...)$ and $\tilde{c'} = (\tilde{c}_0, \tilde{c}_1, \tilde{c}_2, ..., \tilde{c'}_T, \tilde{c'}_{T+1}, ...)$, if $\tilde{c}$ is preferred to $\tilde{c'}$ at time

preferences are constant and taste does not change over time. The structure also implies *b) a stationarity of preferences*[2], which, in Koopman's (1960, pp. 294) terms, is a property that *"the passage of time does not have an effect on preferences"*.

Epstein (1992) actually classifies different preference classes according to their time consistency properties: 1) the functions allowing changing tastes, 2) the ones with dynamic consistency and regret and 3) the ones with dynamic consistency, but not allowing the feeling of regret. Those in the second group violate the above-mentioned weak recursivity by the definition. The ones in the third group are weakly recursive including recursive utility and also expected utility as a special case. Of these two, the EU formulation is indifferent to the timing of the resolution of uncertainty whereas for the RP formulation the timing of resolution matters. A model by Selden and Stux (1978, cited by Epstein 1992), extending Selden's (1978) model to multiple periods is part of the second group. The model has constant tastes, but it violates weak recursivity, thus it imposes dependence of preferences upon unrealized alternatives and thus a possibility of regret. Epstein and Zin (1989) construction of recursive utility specification is included in the third group, although partly based on Selden's groundwork.

As a summary, we can conclude, that the basic idea in using recursive preferences follows the work of Koopmans' (1960) and Kreps and Porteus (1978a, 1978b, 1979) and Selden (1978). In the case of stochastic future consumption, the utility function in $W$ is simply replaced by the certainty equivalent of a random future utility. These preferences are parameterized independently in the two studies by Epstein and Zin (1989) and Weil (1990).

## 2.3.2 Parameterizations of Recursive Preferences

In parameterizing the class of these preferences the authors restrict the aggregator function $W$ to be of CES form whereas the condition for a class of mean value

$t+0$, then intertemporal consistency of preferences requires that the continuation $(\tilde{c}_T, \tilde{c}_{T+1}, ...|I_T)$ is also preferred to $(\tilde{c'}_T, \tilde{c'}_{T+1}, ...|I_T)$ at $(T|I_T)$. By ruling out the possibility of regret, the class of admissible intertemporal utility function is further narrowed, and due to these restrictions the utility function $V$ can be said to be weakly recursive.

[2]The stationarity of preferences property is mainly a result of postulates P3 and P4 in Koopmans (1960). The postulate P3 creates a type of time separability of preference ordering, such that a single consumption vector $x_i$ at one time affects preference ordering only directly by its own virtue, but it does not affect the ordering indirectly by changing a preference ordering of the rest of the program. This rules out effects similar to habit formation and consumption complementarity over time. P3 allows utility to be written as $U({}_1x) = V(u_1(x_1), U_2({}_2x))$. The postulate P4 goes a step further by requiring the preference ordering to remain the same even if the future consumption vector is postponed/advanced in time. Resulting stationarity of preferences allows utility then to be written in the still simpler form as $U({}_1x) = V(u(x_1), U({}_2x))$, without subscripts on $u$ and $U$ inside the aggregator function $V(\ )$. This says that ordering pairs of utility levels (immediate and prospective) as $V(u, U)$ produces an ordering of programs for all future times. These orderings are identical to the one starting at the second period, but advanced/postponed in time.

functionals are left quite general. A general form for the function is then:

$$W(c, z) = [c^{\rho} + z^{\rho}]^{1/\rho}, \ 0 \neq \rho \leq 1, \ 0 < \beta < 1. \tag{2.4}$$

Following this approach the authors parameterization appears as follows:

$$U_t = [(1-\beta)\pi^{\rho} + \beta * [E_t({U_{t+1}}^{\alpha})]^{\rho/\alpha}]^{1/\rho}. \tag{2.5}$$

Here $\beta$ can be interpreted as a subjective discount factor in the deterministic case and $\alpha$ and $\sigma = 1/(1-\rho)$ reflect risk aversion and intertemporal substitution respectively. In this original specification the certainty equivalence part is based on pover function. When $\alpha = \rho$, this coincides with the common expected utility specification:

$$U_t{}^{\alpha} = (1-\beta)E_t\{\sum_{j=0}^{\infty} \beta^j {c^{\alpha}}_{t+j}\}. \tag{2.6}$$

Furthermore, if $\alpha = \rho = 1$, we end up with a common ENPV formulation. Elasticity of intertemporal substitution and risk aversion are not specified by a single parameter anymore in the general case of (2.5). Therefore, by using the RP formulation one may simultaneously model a coexistence of moderate risk aversion and small elasticity of intertemporal substitution, whereas this is not possible in the traditional EU specification.

The timing of the resolution of uncertainty differs from one sublass to another. In the EU setting agents are indifferent to the timing of the resolution by its very construction. In the RP class the timing depends on the future prospects available and are thus said to have a quasi-timing indifference (QTI) property. Intuitively one would expect an agent to prefer earlier resolution of the uncertainty as that would facilitate better planning possibilities.

Another specification is due to Weil (1993), which theoretically evaluates precautionary savings and the permanent income hypothesis and furthermore finds comparative static results of intertemporal substitution, risk aversion and some other main parameters of the model.

The original RP specification described above is based on power functions. Weil (1993) specifies recursive utility such that the aggregator $W$ is of CES form and the risk part is specified in exponential and by a constant coefficient of absolute risk aversion (CARA) form resulting in the following utility function:

$$U_t = \{(1-\beta)c_t^{\rho} + \beta[-\hat{\alpha}^{-1} * lnE_t e^{-\hat{\alpha}U_{t+1}}]^{\rho}\}^{1/\rho}, \tag{2.7}$$

where $\sigma = 1/(1-\rho)$ denotes the constant elasticity of intertemporal substitution, $\beta$ is, under certainty, the exogenous subjective discount rate, and $\hat{\alpha}$ resembles the constant coefficient of absolute risk aversion[3].

[3]Originally, the parameters in our text correspond to those in Weil's article as follows: $\sigma = 1/(1-\rho) = 1/\alpha$, $\hat{\alpha} = \beta$ and $\beta = \delta$.

One may note several points: *1)* If $\rho$ tends to one, the parameter of constant intertemporal elasticity of substitution $\sigma = 1/(1-\rho)$ goes to infinity, and it would resemble preferences where timing of consumption does not matter. *2)* Furthermore, the author describes a limiting case of $\hat{\alpha} = 0$ to correspond to risk neutrality. *3)* Therefore, the special case of expected net present value (ENPV), can be evaluated by setting the risk aversion parameter, $\hat{\alpha}$ to be (close to) zero, and $\rho$ equal to 1. *4)* Still another limiting case, logarithmic intertemporal preferences, can be estimated if $\rho$ tends to zero (Weil, 1993, pp. 369). According to the author, the specification is well-suited for the analysis of the determinants of precautionary savings [4].

### 2.3.3 Recursive Preference Applications

To date most of the applications in this paradigm have been in the macro-oriented econometric literature. Epstein and Zin (1991) offer an empirical application of the approach testing time-series behavior of consumption and asset returns. The results of the study are intuitive except that the consumers' preference for a late resolution of uncertainty is not easily explainable.

Kocherlakota (1990, 1996) reviews a usage of recursive preferences in connection with intertemporal asset pricing models. In the earlier study, the author has quite a pessimistic view of these new preferences, namely, that even if they are theoretically more general, it is hard to distinguish between them econometrically. Therefore, the author concludes that this preference structure does not have more explanatory power than a common expected utility formulation. In the latter study, the author reconsiders the usage of the preferences and concludes that although they do not explain the equity premium puzzle they may be used to explain a so-called risk free rate puzzle[5]. Duffie and Epstein (1992) have an extensive representation of asset

[4]Epstein (1991), in a brief comment, suggests alternative functional formulation for risk preferences and specifies an additional functional form with a recursive structure utilizing exponential:

$$U_t = \frac{-1}{\varrho} \log[e^{-\varrho c} + \beta e^{-\varrho[-\hat{\alpha}^{-1} log E_t(e^{-\hat{\alpha}\tilde{U}_{t+1}})]}] \ \forall\ \hat{\alpha} > 0, \tag{2.8}$$

where $\varrho$ resembles elasticity of substitution and $\hat{\alpha}$ resembles risk aversion, measured with a coefficient of absolute risk aversion (CARA). In the system,

$$\begin{aligned} \mu(\tilde{U}_{t+1}) &= -\alpha^{-1} log E_t(e^{-\alpha\tilde{U}_{t+1}}) \ \forall\ \hat{\alpha} \geq 0\ , \\ \mu(\tilde{U}_{t+1}) &= E_t\tilde{U}_{t+1} \ \forall\ \hat{\alpha} = 0. \end{aligned}$$

The author states that the specification is an example where intertemporal subsitution does not play a role, but it is risk aversion which matters. The specification is interesting, but its exploration is left for future work.

[5]Equity Premium Puzzle is still an unexplained question: why the difference between the returns to stocks and returns on a risk-free assets, *equity premium* is "too" large. Risk free rate puzzle: although the consumers prefer to smooth their income and although the risk free rate is very low, consumers still save "too much".

pricing theory using RP structure.

One of the most recent generalizations of the RP structure is by Epstein and Melino (1995). The authors adopt the already common CES specification for certainty preferences (the elasticity of intertemporal substitution), but the risk preferences are handled nonparametrically, just with qualitative restrictions. The result is an overall semiparametric function to be estimated. The model is then applied to a joint process governing growth and asset returns. As a result, the authors show that actually under RP, there is no equity premium puzzle at least involving first moments. The authors also emphasize the danger of parameterizing the risk preferences, as the "right" form is never known.

Basu and Ghosh (1993) apply a NEU-maximizing approach in a standard Sandmo-type two period savings model. They assume an agent to behave according to Selden's (1978) OCE preferences, and they look at optimal saving under uncertainty. Although under NEU modeling it has been found that both intertemporal substitution as well as risk aversion affect saving decisions, Selden (1978) and Weil (1990) have shown that the qualitative effect of capital risk on the level of saving is a result of intertemporal substitution alone, not due to risk aversion. Basu and Ghosh inquire about the robustness of this argument by comparing alternative risk characterizations, namely the traditionally used mean preserving spread (MPS), first order stochastic dominance (FSD) and second order stochastic dominance (SSD), in order to determine if the result of indifference on risk aversion is just due to a simplistic characterization of risk. The authors conclude, that indeed to be the case in their study: none of the above characterizations let risk aversion affect the level of savings, but more general, higher order stochastic dominance shifter of the risk function made risk aversion matter.

In another study, Basu (1996) uses a hybrid formulation of NEU following Weil (1993), but still in the two period framework. The preferences are iso-elastic in intertemporal substitution, but exponential in risk preferences. The author evaluates a concept of Ricardian Equivalence,[6] and, contrary to several earlier studies, finds it to be a reasonably correct assumption as a result of the simulations done. This is accounted solely for by usage of NEU preferences, which do not impose strict conditions on intertemporal substitution and risk aversion parameters as does the EU formulation. Although both studies utilize NEU approaches, neither one of these studies is an application of recursive utility functions in the sense of Epstein and Zin (1989). Rather they are similar to the study by Selden (1979) as they are only set in the two-period framework. Neither one of the studies mention any possibility of the violation of temporal consistency when using this particular model (see Weil 1990 for citations).

Besides these theory-application studies, Altug and Labadie (1994) and Camp-

[6]Ricardian Equivalence: simple tax cuts do not increase consumption, because people realize that they have to be eventually paid for in some other means.

bell and Koo (1997) have looked at the empirical operationalization of the program. Altug and Labadie utilize the Epstein and Zin (1989) formulation and show how to operationalize the theory into the dynamic programming setting in a consumer's portfolio management problem. They assume a representative consumer with recursive preferences and with an initial endownment of the consumption good, $A_0$, and the returns to follow a first-order Markov process with a transition function $F$. Then the problem can be written as

$$J(A_t, I_t) \equiv max_{c_t,\omega_t}\{(1-\beta)c_t{}^{\delta} + \beta[E_t J(A_{t+1}, I_{t+1})^{\alpha}]^{\delta/\alpha}\}^{1/\delta} \tag{2.9}$$

subject to $A_{t+1} = (A_t - c_t)\omega_t' r_t$ and $\sum_{j=1}^{N}\omega_{j,t} = 1$. The solution to this problem is a plan that expresses consumption and portfolio choices as a function of the state variables, $A_t$ and $I_t$, consumer's initial wealth and state of the economy respectively. The latter authors compare numerical and analytic approximate solutions of an intertemporal consumption choice problem with recursive preferences.

Unlike in macroeconomics, the applications on resource economics field have not surfaced until very recently. In the use of recursive preferences in the natural resources literature Knapp and Olson (1996a, 1996b) are the pioneers. In their first article, they characterize the problem and use lattice programming to prove that under an optimal management a certain type of steady state can be achieved. In their second study, they concentrate on an empirical groundwater management problem in order to evaluate the applicability of this paradigm and behavior of the particular functional formulation in this case. An additional interest in the studies by Knapp and Olson is the methodological choice: the authors use mathematical simulation whereas in the earlier macroeconomic studies econometrics was always used. The empirical results are somewhat surprising, although similar as in some earlier macroeconomic studies: risk (aversion) does not seem to have a very significant role in agent's action. This could be a somewhat disturbing finding as traditionally so many anomalies in microeconomics has been explained by risk. Therefore further empirical RP applications are called for.

Besides the studies by Knapp and Olson, there have recently appeared two papers utilizing RP. One is a theoretical forestry paper by Koskela and Ollikainen (1998). The authors evaluate forest owners' harvesting behavior in a two period harvesting model under biological uncertainty and when amenity services of a forest stand is valued. Another example is by Epaulard and Pommeret (1998). These authors look at non-renewable resource extraction under uncertainty and test their model empirically.

In the present study, we evaluate a suitability of RP formulation for forest management using mathematical simulation similarly as Knapp and Olson (1996a). Furthermore, we assess the empirical validity of the model using a simulated data set and the same functional specification as above, namely the specification by Epstein and Zin (1989) presented above in the equation (5). Unlike in static context, for recursive utility there are no generalized utility specifications available, and therefore another specification will be evaluated using a model by Weil (1993).

In the analysis we evaluate the results from and the performance of alternative recursive utility specifications for the forestry problem and compare the results to ENPV management. It is especially interesting to evaluate whether the forest cutting decisions seem to be largely affected by risk aversion or if intertemporal substitution is the driving force. If the alternative specifications suggest a dramatically different result for this question, clearly more extensive analysis is in order.

## 2.4 An Empirical Application

The recursive preference (RP) approach is applied here to a case of forestry management. Forestry investments are long term investments with many sources of stochasticity. Therefore, the RP-approach lends itself very naturally for such an application. In practical terms, forestry is modeled as a biomass stock, which is continuously harvested. A similar approach to a forest management can be found e.g. in Montgomery and Adams (1995). A practical example of this could be a stand grown for fuel wood or for pulp processing, where a total biomass volume is the main interest, and where size and age distributions of trees are not as significant. In our model, the harvest returns are assumed to be immediately consumed i.e., there is no capital markets explicitly available[7]. Using this model, the significance of risk aversion and intertemporal substitution are evaluated.

The goal here is to find an optimal management schedule for a stochastically growing forest. Every year a forest manager/owner must decide how much she should cut. At the time of the decision an agent knows exactly the current forest biomass, but she does not know growth for the next year, only an expected growth given the mean and a standard deviation around the mean. This is a dynamic problem which can be solved by dynamic programming.

*Recursive Preferences*, have a built-in recursion structure somewhat similar to that of the dynamic programming methodology. In both cases, an infinite program is written as a two-part model dividing the utility stream into the current pay-off or "felicity" and into expected future pay-offs. This similarity provides a natural connection between the two concepts and thus a step from stochastic dynamic programming with ENPV to a recursive preferences model is not such a great leap as one might first suspect.

We start our empirical application by writing out a theoretical model of the forest owner's utility maximization. In the forestry framework, at time $t$, $s_t$ is a forest stock, harvest, $h_t$, is the control variable, and $s_{t+1} = s_t - h_t + G(s_t - h_t)$ gives an equation of motion. Stochasticity enters into the equation of motion as stochastic growth. The forest owner's objective is to maximize her utility from consumption, constrained by

[7]The consumption is here taken to be equal to forest income. There is no possibility for savings or loans. A model with wealth as a second state variable is a natural extension for this work.

the forest growth process. This results in the following program to be maximized:

$$\max U_1 = W[\pi_1 \quad , \quad \mu(\tilde{U_2})] \tag{2.10}$$

$$s.t.\ \pi_t = (p_t - c_t)h_t \tag{2.11}$$

$$s_{t+1} = s_t - h_t + G(s_t - h_t) \tag{2.12}$$

$$s_t \geq h_t \geq 0, \tag{2.13}$$

where $p_t - c_t$ is a net price multiplying the amount harvested $h_t$. Amount of harvest is always non-negative and naturally less or equal to the current stock. In the objective function, we have current utility as a function of felicity from current income and expected future utility. The first constraint describes the linear profit function used. The second one is the equation of motion for the stock variable, i.e. the growth function. Finally, intuitive constraints for harvest levels are laid out. In this particular case, we have to find an optimal level of harvest, hence determining consumption today and initial stock size for tomorrow given the above objective function and growth function. The resulting model is a time autonomous problem, which can be solved with infinite horizon dynamic programming.

Following Altug and Labadie (1994), given that we can solve the problem (10)-(13) for all initial stock levels, $s_0$, we can then define a so-called value function[8] as a maximized value of the objective function in equation (10). The optimal value function satisfies the so-called Bellman equation, which is a functional equation in the unknown value function. Solution to this functional equation gives the optimal value function for the original dynamic optimization problem. Using the value function and the equation of motion we can then define a policy function which, for each period, describes the optimal harvest as a function of state variable.

This analysis will be carried out with two specifications for recursive preferences described in the previous section: the "original" specification (EZ89) by Epstein and Zin (1989), and the alternative specification (W93) by Weil (1993). In the dynamic programming procedure a base parameter value for a relative risk aversion parameter, $\alpha$ , will be $-0.5$. The same value was used in the article by Knapp and Olson (1996a). In comparison, when using the specifications by Weil (1993) we will use a value for a coefficient for absolute risk aversion (CARA). The numerical CARA values are similar to those used by Basu (1996) who studied proportional tax and Ricardian equivalence utilizing the same functional specification. According to the author's investigation, reasonable values for CARA are on a range $\{0, 2\}$ with this specification. In order to emphasize the effects of risk on management, a larger range is used, namely CARA values of $(0, 2, 10, 20)$. We must note here that the CARA values used do not have any resemblance to the CRRA values used in the EZ89 specification and thus the performance of each specification must be evaluated individually and not compared to each other.

[8]The value function appears as a function $J(\ )$ in the left hand side inside the brackets, in the equation (7). The equation as a whole is called Bellman equation.

The growth function used here is based on a hypothetical data set utilized also in a study by Cawrse, Betters and Kent (1984). These authors specify growth as a function of time (age) and present stock. The volume data was created using the following equation: $\Delta x_t(t, x_t) = ar * t^{-b} * x_t * (1 - \frac{x_t}{K})$, where $ar = 0.22871$, $b = 0.2909$, $K = 410$ and $x(0) = 410/118$. We use their growth specification and simulate our own data set. We then take this data set as if it was a real data and fit a growth function to it, however, only as a function of the previous years stock. The resulting, logistic growth specification we use in the dynamic optimization is as follows:

$$\Delta x_t = 0.072816x_t - 0.00018599(x_t)^2 \tag{2.14}$$

The constant net price used in this study equals 15 and the discount rate is taken to be 0.05.

## 2.5 Results

Before introducing stochasticity into the problem, we calculate the maximum sustainable yield -level (MSY), and Fisherian optimal biomass and harvest levels for this system. Although MSY solution is only based on system's biological characteristics, and Fisherian solution only compares the value growth of alternative assets, the calculation offers concrete information about the problem at hand and about the harvesting options. This helps us also to understand the relative importance of the utility modeling approach itself. For this purpose we assume an interest rate of 5 percent and the particular growth function above. For MSY we simply need to find the stock level for the maximum annual growth and for the Fisherian optimum, we need to find the stock level, for which the annual rate in stock value is the same as the growth of investments on capital markets. In other words, we need to find stock levels for which, given growth $f(x)$, $f'(x) = 0$ and $f'(x) = r$, respectively.

For the MSY we fnd the stock level to be 195.75 and related annual harvest to be 7.13 units. Similarly, for the Fisherian optimum the stock level should be 61.34 with annual harvest equaling to 3.77 units. In the deterministic case discounting has quite a profound effect on management. The MSY stock level is three times larger compared to Fisherian optimum. This further clarifies the importance of finding a proper management rule for forestry and underlines the significance of discussion between foresters and economists during the last 150 years.

Next, we evaluate the results with stochastic growth from the expected net present value (ENPV) optimization. The results are quite intuitive. By the definition, the ENPV formulation simply maximizes future returns from an asset discounted to the present. It does not value timing of consumption or consumption smoothing. Only the amount of consumption, which here also equal harvest returns, matters. In essence, we are only interested in efficient production, and consumption automatically follows from that. This effect appears in an agent harvesting zero amount in the beginning (see the upper part in figure 2.1). In the process, the biomass is left to grow freely the first 14 years. After that the harvesting starts and rises quickly reaching a long term stable harvest and consumption levels in 4-5 years. Similarly, the biomass stock reaches a long term stable level. Thus in about twenty years the system reaches a long term stability.

The long term stable forest stock size is about 57.7 units, and the respective level of harvest is about 3.4 units. This level of stock is connected with quite a low standard deviation, less than one unit, or about 2 percent. However, the standard deviations in harvest and profit levels are close to 30 percent (lower part in figure 2.1). Such results are supported by the intuition: the ENPV case is "production oriented", and consumption preferences do not enter to the optimization procedure at all. The timing of consumption is not important, only the level of it matters. The level of the stock affects biological production efficiency directly. Therefore, the "production-efficient" stock level (counting for stochasticity) should be reached as quickly as possible by refraining from harvest, and afterwards this ideal level has to be maintained. Consumption is left to adjust in the process. This results in a relatively high level consumption, not much less than in the above deterministic problem, however, with a co-existing high level variation in consumption.

Next, we assess a case, where an agent's risk preferences are still neutral, but where the timing of consumption matters. We use the recursive specification EZ89 by Epstein and Zin (1989), written out in the equation (5). Technically speaking, we adjust the elasticity of intertemporal substitution (IES). The parameter is decreased from infinity to medium-IES, $\sigma = 0.5$, still keeping the risk neutrality assumption (i.e. $\alpha = 1$ ). The effects are significant. Now an agent starts harvesting and thus consumption immediately. This is intuitive as now the timing of consumption matters, and with the particular parameter used, the willingness to substitute today's consumption with consumption in another period is considerably lower than in the previous example. Due to the different consumption pattern, the biomass stock grows slower. Another significant result is that the standard deviation in biomass stock level is now much larger than in the base case, whereas the deviations in harvest and profit levels are clearly decreased. In other words, the biomass level which was earlier kept tightly on its desired level (close to ENPV stock level) is now let to fluctuate in order to provide a steadier consumption pattern. Intuitively, it seems that some productive efficiency is sacrificed in order to reach a preferred consumption pattern.

Finally, comes maybe the most interesting case, where both risk aversion and elasticity of intertemporal substitution are present, i.e., the model is evaluated with risk aversion having the risk parameter $\alpha = -0.5$. The resulting biomass stock levels, and consumption and profit patterns are very similar as in the case with low IES and risk neutrality (see the figure 2.2).Both, qualitatively and quantitatively speaking, the changes from the second case are not very significant. Thus, according to this analysis, risk aversion does not significantly alter the optimal solution.

The qualitatively similar analysis was repeated using a lower IES-parameter, $\sigma =$

Figure 1a. Biomass levels with standard deviations under E(NPV)

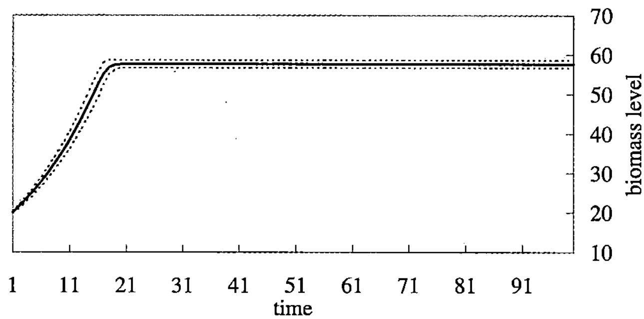


Figure 1b. Harvest levels with standard deviations under E(NPV)

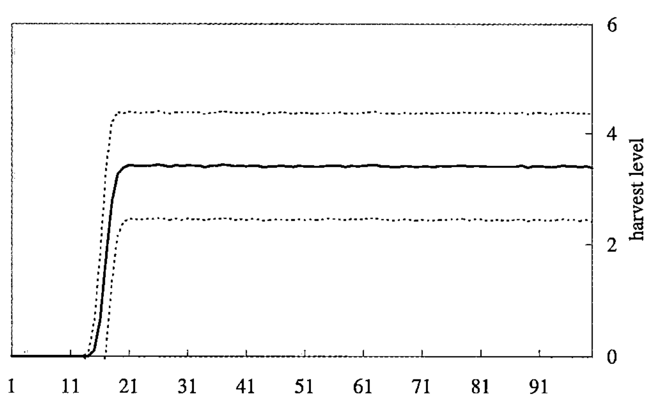


Figure 2.1: Forestry management under ENPV. Expected values and one standard deviation for biomass and harvests respectively.

Figure 2a. Biomass levels under risk aversion and low IES

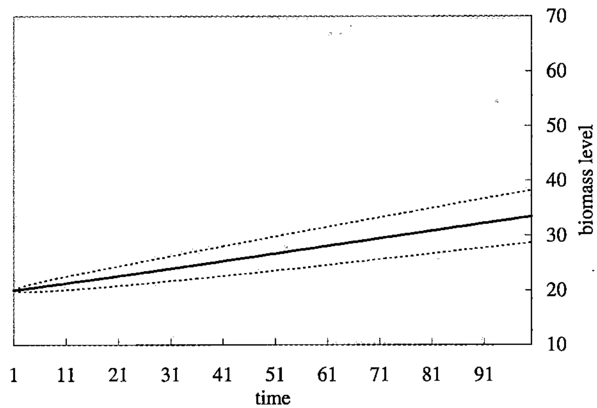


Figure 2b. Harvest levels under risk aversion and low IES

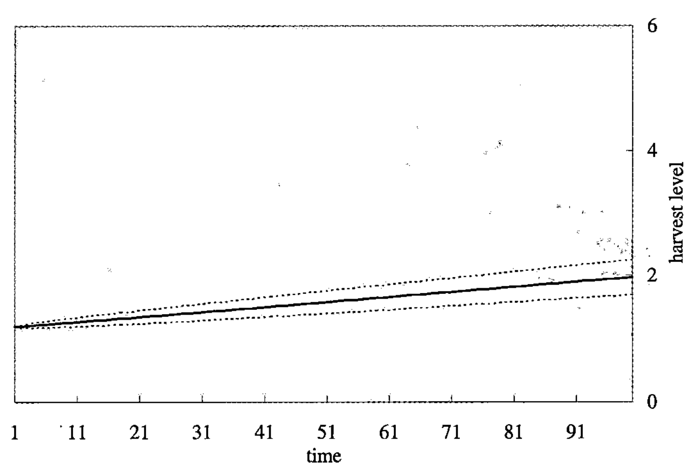


Figure 2.2: Forestry management with Epstein-Zin (1989) recursive preferences, medium IES, and no risk aversion. Expected values and one standard deviation for biomass and harvests respectively.

| IES | risk | x | h | $\pi$ |
|---|---|---|---|---|
| $\infty$ | 1 | 57.68 (0.96) | 3.41 (0.96) | 51.22 (14.42) |
| 0.5 | 1 | 26.41 (3.06) | 1.56 (0.18) | 23.36 (2.71) |
| 0.5 | -0.5 | 26.56 (3.08) | 1.56 (0.18) | 23.44 (2.72) |
| 0.1 | 1 | 21.29 (2.68) | 1.35 (0.16) | 20.24 (2.45) |
| 0.1 | -0.5 | 21.51 (2.71) | 1.36 (0.16) | 20.37 (2.46) |

Table 2.1: Optimal forestry management in year 50 with Epstein-Zin (1989) recursive preferences and standard deviations in parentheses.

0.1. This low-IES model was first evaluated assuming risk neutrality and then with $\alpha = -0.5$. Results seem to be very similar as in the second simulations. We can see that in the age of fifty (see the table 2.1 below), the ENPV-biomass stock level is aforementioned 57.7 units. For the cases of medium-IES and low-IES, the optimal stock levels in the age of fifty are now 26.5($\sigma = 0.5$) and 21.5($\sigma = 0.1$) respectively. It can be noted that tightening the IES still further has a significant effect on optimal management. In fifty years time, the optimal stock level at the lowest IES is now over twenty percent less than the value from the medium-IES. It can also be noted that the stocks are far from the steady state levels and that stock standard deviations are smaller the lower is the IES value. The levels of harvests at the age of fifty are affected in a similar manner: a change in IES affects the levels considerably, for ENPV, $\sigma = \infty, h = 3.41$, and for recursive utility, $\sigma = 0.5, h = 1.56; \sigma = 0.1, h = 1.35$. Also the standard deviations are decreased considerably. Naturally, the similar pattern can be found when the annual profits are evaluated. In turn, risk aversion seems to affect neither stock levels nor harvest or profit level significantly in either of these cases.

When comparing to the ENPV optimization, it is interesting to note, that the biomass growth, harvest and net returns, all three have crossing patterns at age of about 20 years. Initially, all these three levels in ENPV case are very low in first 14-15 years, but after tventy years they are higher than the optimal in the medium-IES and low-IES management. Looking at the stock development the main difference is, that even over time of hundred years, the medium-IES and low-IES optimal stocks do not reach the steady state. The stocks are still below of those of the ENPV solution and growing. It would be interesting to see, if the medium-IES and low-IES case stock levels actually converge to those of the base case, or if their long run stable levels stay lower permanently.

Next, we study the harvesting problem using the alternative specification (W93) by Weil (1993, see equation 8). First, we will evaluate the case where the manager is risk neutral, but she has medium level of IES. Because of the infinite elasticity of subsitution, the manager prefers to have some consumption, and thus harvesting on each period, thus the harvesting starts right in the beginning. The stock development is therefore only moderate, stock level reaching 33 (from 20) in hundred years. The harvest level after hundred years is 19 units per year i.e., about 6 percent of the stock annually. The standard deviation of the stock is approximately 15 percent and the standard deviation of the harvest is little less than 15 percent annually.

After that comes the most interesting case, where both positive risk aversion and low IES are present. We evaluate three cases, where $\hat{\alpha}$ is given values, 2, 10 and 20. The value 2 already resembles quite high risk aversion and the values 10 and 20 describe very high if not exessive risk aversion. The similar simulations were evaluated as above, and the main conclusion is that the risk aversion does not affect the optimal behavior significantly. The changes in stock level and harvest level were less than one percent, when the risk aversion parameter was increased from zero to 20. Practically, this means that the risk aversion is insignificant in determining optimal harvesting in our case. We evaluated also a few cases, where the IES parameter, $\sigma$, had a medium value equal to 2, and risk aversion parameter was again adjusted between zero and 20. This analysis produced results fitting between the ones discussed here: the harvesting was always positive, thus it was in the beginning higher than in the ENPV case, however, in the end of the period the harvesting was lower than in the ENPV case. This follows well the intuition and thus reinforces the analysis.

These above simulations were similar to EZ89 analysis, just a different functional specification was used. Additionally, we evaluated one case unique for the W93. In that analysis, we considered optimal management when the intertemporal substitution is infinitely elastic, and risk aversion goes from zero to extremely high levels ($\alpha = 20$). This can be interpreted as a situation, where timing of consumption does not matter, but where the forest manager is risk averse additionally where risk markets are non-existent. Because of the high IES, the system reaches the steady state quickly, similarly as in the ENPV case in less than 20 years. This in turn allows us to examine the steady state values of the stock and the harvest and brings risk aversion into the picture. One may notice (see the figure 2.3), that the risk aversion affects significantly the steady state levels. With very high risk aversion, ($\alpha = 20$), the steady state stock level is reached in about 17 years, and the level is approximately 52 In turn, with the risk neutral preferences, the optimal management follows a path where the steady state is reached also in about 17-18 years, but the steady state level is about 58. In this analysis, high risk aversion causes the harvest levels to be about ten percent higher compared to the case with risk neutrality. Standard deviations in both cases are qualitatively similar: the harvest level is allowed to widely fluctuate in order to adjust to stochasticity and to be able to hold the stock level tightly around the optimum.

It can be thought that the forest stock is used as a productive capital here, and the production process is inherently stochastic. Given that the manager is risk averse i.e., she dislikes the risk, she does not want to hold a large (productive) capital stock

Figure 3a. Biomass levels under risk neutrality and high IES

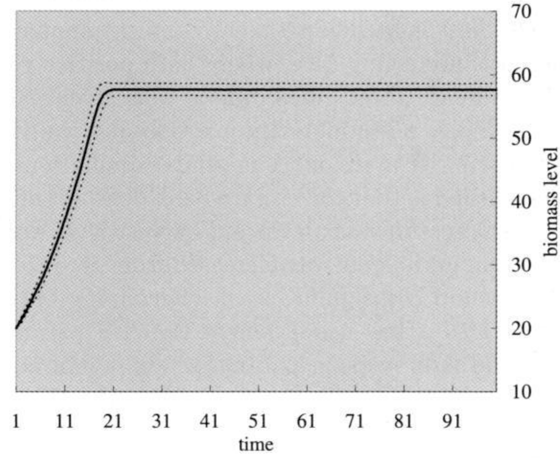


Figure 3b. Biomass levels under high risk aversion and high IES

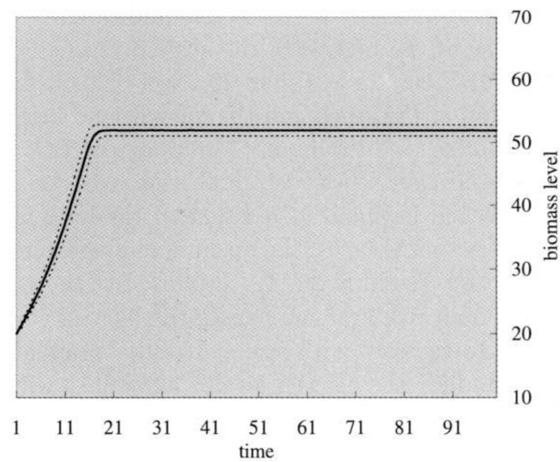


Figure 2.3: Forestry management with Weil (1990) recursive preferences and alternate levels of IES and risk aversion. Expected values for biomass and harvests respectively.

in stochastic production. Instead, she prefers to consume more in the beginning and thus to reach the lower steady state in an early stage.

Looking at the analyses done here with alternative specifications, we can conclude that in our case risk aversion does not significantly affect the forest management in general. However, it affects the steady state levels in a manner expected: high risk aversion makes one consume earlier and hold smaller stocks. In turn, the IES profoundly affects the management: with low IES, the harvesting starts at the first period, as the manager does not want to postpone the consumption for the sake of overall higher biological productivity, whereas in the case of infinite IES, consumption is sacrificed in the beginning for a gain in biological productivity.

The management problem evaluated here differs considerably from those of Knapp and Olson (1995, 1996a). In this study, the stochasticity affects directly the growth of a stock, and thus potential consumption, and also the control variable affects the profits directly. In the groundwater study by Knapp and Olson (1996a), the inputs of production (surface water) were stochastic, and adverse effects of the stochasticity could be minimized by drawing irrigation water from an underground pool. In other words, the control was used to stabilize production levels. Despite the differences in the models, we arrive at basically the same conclusion as Knapp and Olson (1996a), namely, that risk aversion does not affect optimal management significantly; however, the intertemporal elasticity of substitution does cause a significant difference in optimal management.

As was mentioned earlier, Basu and Gosh (1993) in their study investigated whether the previously found irrelevance of risk aversion in the context of recursive preference formulations is robust. The authors utilized Selden's (1978, 1979) OCE nonexpected utility formulation to test the irrelevance result with more diverse risk characterizations. They acknowledged the irrelevance result in a case of mean preserving spread in random returns. Additionally, they showed that even under an increase in risk characterized by a First Degree or a Second Degree Stochastic Dominance shift of the distribution function, the effect is independent of the risk aversion coefficient. However, they pointed out, that the coefficient of risk aversion plays a very fundamental role in characterizing an increase in risk that can be represented by higher order stochastic dominance shifts of the distribution function. Therefore, we cannot draw conclusion from our study that risk aversion does not matter at all, only that it does not seem to affect the management behavior in our case. Quite the contrary, this is one important aspect to be kept in mind when designing further extensions to the study at hand.

Similarly, Koskela and Ollikainen (1998) using the approach by Weil (1993) studied theoretically the effects of biological uncertainty on harvesting behavior when forest owners have preferences over harvest revenue and amenity services of forest stand. They reported that a rise in multiplicative forest growth uncertainty increases current, but decreases future harvesting, which they interpreted as evidence of a precautionary behavior. For additive growth risk the authors found harvesting to remain unchanged. Reflecting our results with the results of Koskela and Ollikainen (1998) and Basu and Gosh above, the need for a further study with more diverse risk descriptions is underlined. In our case, the results show that risk aversion clearly has a secondary importance in optimizing harvest scheduling compared to intertemporal substitution. However, the steady state value of the optimal stock level seems to be directly connected to the size of the risk aversion parameter.

## 2.6 Summary

In this paper, we present a non-expected-utility measure, namely recursive preferences, to be used in resource management. This methodology can contribute to the forestry literature, as it provides an alternative usable in stochastic, intertemporal frameworks with risk averse agents. Dynamic studies including risk aversion have so far been very scarse, possibly due to a lack of suitable methodology. We hope that this approach, so far only popularized in the macroeconomic literature, enables more fruitful research in forestry as well as in resource economics in general. Not only does this new method have a strong theoretical bases, but it also yields broader empirical results than the traditional alternatives. The approach reveals the motives behind the actions, namely, it shows whether risk aversion or intertemporal substitution is driving the agent's decision.

In this paper, we first review traditional forestry and recursive preferences studies. Next, we apply two alternative recursive preference specifications to our own data. Finally we evaluate the empirical results and also the performance of the alternative specifications in order to gain a better understanding of the applicability of this method to resource problems. We are especially interested in empirical results on the importance of risk aversion in agent's decision making, as in previous studies, the effect of risk aversion has appeared to be surprisingly small.

After the introduction, we compared the results from the RP formulations to the traditional ENPV optimization. The results are quite different. The main issue is the scheduling of harvesting and thus consumption and stock development. In the ENPV model consumption is postponed in the beginning for some 15 years in order to bring the stock level to a steady state level as quickly as possible. Only after that is the harvest started. After the start, the harvest reaches its steady state amount in a couple of years. In the RP model with inelastic intertemporal substitution, harvesting is started from the beginning. This causes the stock to grow considerably slower, and thus the stock appears to be far from its steady state values in year fifty. This is due to intertemporal substitution, as the scheduling is quite similar in the case of risk neutrality as well as in the case of quite high risk aversion.

This brings us to the point of motives behind the particular management actions. According to our analysis here, the risk aversion seems to have an insignificant effect on management profiles. Whereas the intertemporal subsitution has quite a profound effect, and the effect is further strenghtened when the IES is lowered, the risk aversion does not seem to cause much of a change to optimal management, even if it is increased to unrealistically high risk aversion levels.

Comparing the specification by Weil (1993), these effects on managment profiles remain the same. However, when investigating the case with infinite IES and high risk aversion we found that the strength of risk aversion affects the time the steady state is reached and the resulting level of the steady state stock and harvesting levels: the higher the risk aversion the faster the steady state is reached and the lower the resulting steady state is. This can be explained intuitively, that the more the person dislikes the risk the smaller stock she wants to leave to be affected by uncertainty.

The results of our study further support previous findings that risk aversion is not a significant motive behind actions of a manager of natural resource stock when analyzed in RP framework. However, we were not able to pinpoint a driving force behind this somewhat surprising result, thus the issue still needs more investigation.

This research can be extended in many ways. A natural next step is to find a management schedule using a clear cutting option and allowing for thinnings. Conceptually this would require functioning capital markets, which would allow managers to save and/or loan money for consumption during the periods of zero harvest. The possibility of saving and lending would allow also clear separation of production and consumption, and thus the ENPV case would possibly not differ as significantly from the two other cases as it does now. Another technical extension could look at more complicated growth patterns, such as an optimal management plan for coppicing tree species.

Another path to follow would be to include a broader appreciation of forest stands, i.e. to evaluate a management schedule when a stand yields some non-pecuniary benefits. Methodologically the most interesting issue would be to further analyze the effects the effects of the particular parameterizations and forms of utility functions. For an econometric study, it would be interesting to be able to define a more general functional specification, which could be better used for evaluation and testing of alternative specifications.

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# Essay 3

# An Empirical Policy Test of a Calibrated Farm Model

Recent developments in agricultural policies in the western world require increasingly sophisticated analytical methods for their evaluation. In this study, we build a detailed farm level production model capable of reproducing farm specific effects of diverse agricultural policies. Specifically, we construct an empirical farm model and calibrate it to a data set for a policy analysis.

The purpose is to evaluate the program for the Finnish agricultural sector. We use farm book keeping data from Finland for the years of 1989-1997. The data is a subset of the EU-FADN data collection system. Positive Mathematical Programming (PMP)[1] is used as a vehicle in the exercise.

The PMP-entropy approach was chosen, because we want the program to be able to describe different farms in very different regional conditions, and because several non-linearities and discontinueties exist in the production environment due to complex agricultural policy measures in place. The PMP approach is especially well suited to the evaluation of the Finnish EU-membership as the change in the production environment occured only recently, and therefore, an extensive data set is not available for the analysis.

The PMP procedure is utilized in order to account for the effects of certain non-market constraints present in farm production guiding farmers behavior. In the process, we also utilize maximum entropy (ME) formulation to handle data deficiencies common in production data sets. With the ME we can reveal cross-effects of different crops in the cost function.

[1]PMP model is a nonlinear, mathematical programming approach used to model agents' decision-making situation when asymmetric information occurs between agents and a modeler. The model is flexable such that it can be calibrated into collected data, and thus linked into a particular place and time. The approach was developed at UC-Davis by Richard Howitt (1995a, 1995b).

## 3.1 Introduction

This essay describes the construction of a calibrated mathematical programming model for a farm. The purpose is to construct a detailed farm model capable of differentiating over farm types and environmental conditions when used for evaluating agricultural policies. The model is fitted to Finnish farm level data for the years 1989-1994 and then tested out-of-sample for the years 1995-1997. After the model construction, we evaluate its behavior, and its ability to predict land allocation depending on the aggregation level of the data.

In European agriculture, one of the underlining current movements is a transformation from traditional demand side agricultural policies towards more supply side oriented policies with specific features depending on the farm type and each farm's local environmental conditions. Such a development is especially profound given the new agricultural policies of the European Union (EU). In practical terms, the development is characterized by voluntary measures offered in many EU countries, especially for environmental protection and for provision of public goods from agriculture. Over this past decade, EU has intentionally lowered agricultural product prices, and in some cases price decreases have been compensated by provision of direct subsidies. The change is partly a deliberate move towards decoupling of subsidies from production. As a result, the agricultural policy menu has become more complex when compared to traditional system, which was dominated by border control and price supports. This in turn, creates new demands for agricultural policy analysis, and thus policy analysts are confronted with an increasing demand for more flexable and easily modifiable tools for the analysis.

These general policy changes prompted this study, namely the quest for suitable research tools for policy making in this new era. The aforementioned changes have been felt strongly on the Finnish agricultural sector and in the Finnish society. Finland only recently joined to EU, and the society is still adjusting. Agricultural production in Finland was highly protected and the change into the CAP was quite significant. The development of the new policy evaluation tool is complemented with a test, where it is rewieved how well the new tool works in today's agricultural policy setting. Technically, the work is a joint application of two methods recently introduced into the production economics: Positive Mathematical Programming (PMP) and Maximum Entropy (ME). Specifically, the PMP-ME procedure suggested by Paris and Howitt (1998) is used. In contrast to Paris and Howitt (1998), we test the model construction with several years of data. The program is modified to handle several years, and it also accounts for zero observatons in the data set.

The PMP technique was published only recently, by Howitt (1995a). The insight in the approach is that there are many nonlinearities in an agricultural production system, constraints which, how ever real their are, do not appear in a market place and thus cannot be observed by a modeler. However, firmly believing in the rationally acting farmer, the effects of those nonlinearities must show in annual production decisions of a farmer, and therefore, one may learn about these effects by observing farmers production behavior and input choices. Howitt (1995a) describes the technique, and shows how to reveal the effects of these constraints in farmer's quadratic cost function. In another article, Howitt (1995b) extends the model into a case of a CES-function. Although the technique itself was only recently published, practioneers have adapted the procedure earlier and thus several empirical applications utilizing PMP exist (Kasnakoglu and Bauer, 1988; Horner et.al., 1992; House 1987; Hatchett et.al., 1991; Rosen and Sexton, 1993; Paris and Arfini, 1995; Burke, 1995).

The procedure for PMP is as follows: First, an LP-model is built and constrained to exactly replicate the base year observations. The results from this LP-model provide us dual (shadow) values for fixed factors and a second set of dual values associated with calibration constraints on crop production. In the second stage, using both sets of the dual values from the calibrated LP, an additional implicit cost parameter reflecting hidden costs e.g., heterogeneous land, is constructed. This parameter is in turn utilized in building a nonlinear programming model. By construction, this model replicates exactly the base period results, now without calibration constraints. Furthermore, the model can be tested "out-of-sample" and used to predict future outcomes and policy changes. Desired policy simulations can be evaluated using sensitivity analysis on the nonlinear model. For instance, effects of price changes and quantity restrictions can be evaluated.

When farms produce several different crops like in our case here, the analysis is more involved and a more complete method than traditional PMP is in order (for multi-output production model see e.g. Just et. al., 1983). In our case, in order to better account for multiple outputs, we apply a recent PMP formulation added with a maximum entropy (ME) feature. The PMP-ME works as the PMP, however, cross-effects of different crops can be recovered using the ME formulation, whereas in the traditional PMP model cross effects are assumed away. This allows more detailed analysis, and produces more realistic policy evaluations.

The PMP-ME procedure is used to calibrate a mathematical model to observed farmer behavior. The purpose is to construct a versatile model, and then to test, how well it forecasts farmers' land allocation and crop choice. Our panel data covers some 36 crop farms for the years of 1989-1997. It is a sample from the Finnish version of the EU-FADN data set based on Finnish book keeping data set going back eighty years to the 1920's. These data are excellent source of detailed farm level information and especially suitable for our application.

The main objectives of the study are *1) building of an empirical farm calibration model, 2) test the model's ability to simulate effects of policy changes at different levels of aggregation, and 3) evaluate the results from the model by comparing them to observed results.*

The study starts by describing the Finnish agricultural policy from a layman's perspective, how the policy was exercised before EU-membership, and how it changed due to the membership. The large conceptual and operational policy-change from EU membership is further analyzed in the next section, where consequences of the change are analyzed from a point of view of an economic analyst. It is pointed out, how very difficult it is to model agricultural production in such a situation. The modeling difficulties due to hidden costs resulting from non-market constraints and nonlinearities in the production environment, as well as due to deficiencies in data collection are clarified. In the following part, econometrics and mathematical programming are reviewed from an economic point of view. As a result of this discussion, Positive Mathematical Programming emerges as the most appropriate tool for the analysis in this study. After that concepts in PMP and ME are reviewed, the reader can better appreciate the chosen methods. This is followed with a description of the data. Finally, simulation excercise and results from it and the conclusions are presented.

## 3.2 Finnish Agriculture and Agricultural Policy on the 1990's

Finland is located between 60° and 70° latitude levels, and therefore, climate for agriculture is very harsh. The growing season in southern Finland is about 180 days and in the northern part of the country 130 days. Long daylight compensates cold climate for grasses, but in some ways may be even difficult for crops. Due to a cold climate, some common animal feed crops like corn and alfa-alfa cannot be grown in the country.Despite the unfavourable conditions Finnish agriculture has been succesfully engaged in international trade. For example, it was competitively exporting butter to England in the first half of the 20th century. Besides the cold climate, soils are poor, fields are scattered due to variable terrain, divided by parcels of forest and waterways. Nature provides farmers with ample amount of moisture, which, however, comes somewhat unbalanced, mostly in a harvest time, not in the beginning of a growing period when it is needed. On the other hand, due to the cold climate, agricultural pests and plant diseases are more easily controlled than in some warmer regions, and therefore less chemicals are needed. Also due to relatively sparsely populated agricultural areas, agricultural soils are barely tainted by heavy metals or other toxins. The most suitable crops/plants in the regions are grasses as they can utilize long period of daylight. This emphasizes the profitability of milk production. Pork and poultry production are also profitable enterprices as their activities are largely indoors and thus insulated from the natural environment. In principle, livestock production could compete with EU-production provided price of feed stays reasonable, and environmental norms do not make production prohibitively costly.

Besides the unfavourable climate, the structure of Finnish agriculture is not especially suited for large scale production benefitting from scale economies. The aforementioned non-uniform geography is just a one reason for a low structural development. The land reform in the 1920's, and the loss of 10 % of agricultural land


Figure 3.1: Average length of the growing season (average temperature of the days over +5° C) in Europe in 1960-1990. Source: Finnish Meteorological Institute.

and the need of rehabitation of large number of agricultural families after the second World War have slowed down the enlargement of farms in Finland (Kettunen, 1992). According to Kettunen (1992), there were about 200 000 farms in Finland in 1990, and average size of a farm was small, 13 hectars. Of the total, some 70 000 farms were managed by a full-time farming family, and average size of these full time farms were about 19 hectars. Still in the 1960's both livestock and crops were produced on farms, however, current farms are more specialized. Most of the farmers own also some forest, which was traditionally seen as a bank and an insurance providing capital for large investments and insulation for agricultural production shocks.

The significance of agriculture in the Finnish economy has declined over the years. It was still about 10 percent of the GDP in the 60's, it fell to 4 percent in the beginning of the 90's, and it has further decreased since (Kettunen, 1992). Despite, or due to its size, the agricultural interest groups have traditionally succeeded quite well in agricultural policy making. Aakkula (1990) discusses about reasons behind the relative succes, one reason being the especially high value based on food security, due to recent war time experiences.

### 3.2.1 Agricultural Policy Development

Finnish agricultural policy has been evolving in very same manner as agricultural policies in western Europe and in USA. In the last thirty years, agricultural policies have become increasingly detailed and have expanded in their coverage. The agricultural policy has been characterized by several, often conflicting goals and high emotions. Kettunen (1981) lists the agricultural policy goals as follows: i) food security/self-sustainability, ii) reasonable producer incomes and consumer prices, iii) evolving structure of agriculture, and iv) rural livelyhood. These goals are supported by production policies, price and support policies, structural policies and regional policies.

Active agricultural policymaking started in Finland on 1960s, when milk production had reached and passed domestic consumption. The set of agricultural policies grew during the 1970's and 1980's creating a complex net of economic incentives and disincentives for production. The main production subsidy measures were price support systems, complemented with high border control in order to insulate the sector from the world market. Production restraints were mainly managed by command and control systems, like milk quotas and animal holding permits and set-asides, however, also payments for export subsidies were collected from farmers. Kettunen (1993, pp. 17) notes that in many aspect late Finnish agricultural policy and the CAP were very similar, however, practical implementation of the policies differ in many respect. The main emphasis in both were on administered prices. Supply and foreign trade have been regulated in order to keep the prices at a desired level.

In the beginning of the 1990's, administrative price setting was the core of the Finnish policy. Producer prices were negotiatiated and agreed upon in co-operation by the state and farmers unions. The negotiation parties first agreed on a lump sum for the total return. This amount then was divided to different groups using several different methods, according to a formula agreed in the negotiations. The methods included e.g., target prices (market prices) and price and income support. At the time, direct supports were increasing whereas the product prices were quite stagnant. The total state support paid through the state budget was about 15 percent of the total return of the agricultural sector (Kettunen, 1993).

In practice, production policy in the Finnish agricultural policy meant supply control. The government set certain production (export) ceilings, and any exports above the ceiling and subsequent export subsidies had to be financed by the farmers. Additionally, a compulsory fallowing was in use, requiring each farm to set-aside 15 percent of the arable land to be eligible for a certain direct support, and to avoid an area-based penalty. Set-asides above the required amount received a fallowing payment. Production of milk and eggs were regulated by individual production quotas. The only production policy measure designed to encourage production was a premium paid for heavy carcasses in beef production (Kettunen 1993).

Structural policy was designed to enchance the structural development of the agricultural sector. Mainly it was based on loans and direct aid for aquiring farm enterprises. Additionally, investments on machinery and other implements were assisted through subsidized loans. Recently, the assistance of complementary farm-based enterprises were supported in order to diversify the farm enterprises. These rural enterprises included farm-tourism, small scale service and production enterprices, etc. Some of the policy measures in the above three groups worked against each others due to somewhat opposite and disagreeable policy objectives in the first place.

At the time, agricultural policies were under fire for many reasons. The society had been becoming more urban over time and agricultural subsidies were receiving more and more criticism from tax payers and at the same time weights of competing political parties changed in favour of non- agriculturalists. The highly publicized PSE-calculations for agricultural subsidies painted Finland as one of the highest subsidizers. Food prices were perceived high by many consumers, and this was underlined by the very harsh recession Finland experienced in the beginning of the 90's. The negative environmental effects of farming were also critized more loudly at the time. Besides these internal effects, GATT- Uruguay round negotiations caused increasing pressure on agricultural policy practices. The economic situation in the country was very difficult, as the prevailing depression was the worst since 1930's. Therefore, although lower food prices were seen as an important consumer concern, agriculture was also seen as a stable provider of employment. This was an additional reason later, in the EU negotiations, to require a (temporary) cushion for agricultural adjustment. Alternative employment possibilities were extremely scarce in the countryside, and this still applies. This may be one reason, that more drastic structural change still has not happened on the agricultural sector.

One of the most significant changes due to EU-membership was expected to be the change from domestically negotiated prices into the price system administered by the EU. Secondly, Kettunen (1993) notes the significant change in the budgetary system: after the EU membership the agricultural support is paid from the EU budget, and subsidized exports are a responsibility of the EU. After joining the EU consumer concerns seem to have been lowered, partly due to less obvious outlays of agricultural subsidies in the domestic budget and significantly lower retail prices of food.

### 3.2.2 EU-membership and CAP

Finland joined to European Union in the beginning of 1995. The discussion on EU-membership started in the beginning of the 1990's, but it peaked rapidly in 1994. The process was emotion-filled and controversial. Especially, farmers union, agricultural sector and people living in the countryside saw themselves as loosing the most.

The settlement on agricultural issues as a part of the Accession Treaty of Finland to EU was agreed upon 1994. The issues in the treaty can be divided to three main classes: 1) production issues, 2) level and regional distribution of support and 3) transition period. The goal was to have the current distribution of incomes unchanged, even if the levels would need to be lowered (Kettunen and Niemi, 1994, p. 34). This goal, combined with a new structure of CAP measures, required new national measures to be flexible and complementary to CAP measures. This is one reason that a more detailed analysis method is now required.

Kettunen and Niemi (1994, pp. 30, 33) list the contents of the EU support package as follows: 1) CAP reform support, 2) Less Favored Area (LFA) support, 3) agri-environmental support (EU 2078 Program), 4) National support. The national support consists of the 1) agri-environmental support (domestic part), 2) long-term nordic support, 3) national special support in Southern Finland, 4) support for young farmers, 5) seed production support, 6) degressive transition period support (at the most 5 years), and 7) transportation support. The payments are regionally differentiated according to the zone (A, B, C1-C4) where a particular farm is located (see the figure 3.2).The regions are categorized according to a production type. Grain farms were especially expected to be in danger. Cost savings on those farms were not as visible as in livestock production, and it was suggested that full-time grain farms may practically disappear from the Finnish agriculture, and be replaced by hobby farms and part time farmers. (Marttila, 1993, pp. 64-65). Kettunen and Niemi (1994) also evaluated the effects from the EU settlement and their results were similar. The authors found mixed results about the profitability changes. According to farm model calculations (Kettunen and Niemi, 1994, pp. 50) the profitability is affected very differently depending on the farm type and the region. This seems to be in a stark contrast to the aforementioned distributional objective. Due to low producer prices and the large reliance of direct subsidies, it was seen inevitable that the support was capitalized into price of land and thus hindered structural development.

The agricultural production has continued mainly unchanged during the mem-

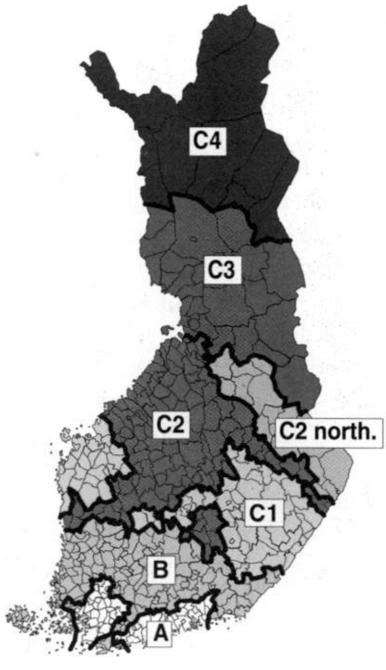


Figure 3.2: Agricultural support zones in Finland. Source: Finnish Agricultural Economics Research Institute.

bership. There have been large difficulties in pork and egg production, where the prices have fallen tremendeously. Another concern has been a relatively very large proportion of direct subsidies in farmers income, and their effects on farmers decision making. Consumers seem to appreciate domestic production more than before and similarly tax payers have also started to accept and appreciate the value of numerous non-market goods provided by agricultural sector.

## 3.3 Methodology

As a result of the complex agricultural policies described in the previous section, policy modeling of agricultural production has become increasingly challencing. Generally, agricultural production issues are examined either using econometric methods or a mathematical programming. Both methods clearly have their own strong points depending on the question and data at hand and of course they can be used jointly together.

### 3.3.1 Modeling Alternatives

Econometric models are often considered to have a more positive character whereas progamming models are thought to be more normative. However, as Colman (1983) points out, in many econometric studies, modelers have had to invoke profit maximization in order to obtain reasonable results. If the assertions are used, their applicability should be tested as a part of a modeling sequence. By their very construction, econometric models are very data intensive requiring a large amount of statistically suitable observations. Still, due to violations of some of the statistical assumptions, econometric models do not always explain the past, nor do they predict the future satisfactorily. Scarce data and the subsequent lack of degrees of freedom may prevent the evaluation of cross effects between commodities. Choosing a "right" functional form is an additional hurdle, which does not have a very well developed theory. A third potential problem is caused by abrupt changes in policy regimes, which are often hard to model when using econometric models (see Shumway and Chang 1977).

There are several examples of good econometric studies done on production economics of an agricultural sector (Just, 1983; Lopez, 1980; Shumway, 1983; Weaver, 1983), however, most of them utilize highly aggregated data sets. There are also some, mainly European, examples of econometrical production studies using farm level data (Moschini, 1988; Thijssen, 1992a; 1992b; Ryhänen, 1994). Just et.al. (1983) present a framework for studying of multi-output production functions, where allocations of variable inputs among crops are unobserved. The authors also show that the popular single-equation, multiple-output production function approach is relatively unattractive alternative. Another, distinctive group of farm level econometric production studies are those measuring the efficiency of production (see Dawson, 1987; Dawson et.al.

1991), and productivity differences between farms (Turvey and Lowenberg-DeBoer, 1988). As a result of their study, Turvey and Lowenberg-DeBoer recommend, that the assumption of common production function slope coefficients should not be accepted as a matter of course. This suggests that some more farm-specific estimation procedure have to be found.

Contrary to econometric studies, traditional mathematical programming models have a rigid structure, in which basic behavioural rules for agents are imposed (profit maximization, utility maximization). Traditional programming models have only a tenuous connection to data and thus these cannot describe, or predict specific years. An outcome is just the best possible result to a given optimization problem. Without direct connection to observed outcomes, validation may cause difficulties (see McCarl and Apland 1986, Paris 1981). Since LP models are only able to produce stepwise demand and supply functions, they do not describe reality well, and sensitivity analysis may end up being somewhat clumsy (Paris 1989, Paris 1994). Finally, programming models commonly result in a high level of specialization, to a greater extent than that observed in practice. However, in some cases, being independent of specific years, mathematical modeling approach may prove to be the preferred way to build different scenarios concerning future outcomes of alternative policy regimes.

Wossink and Renkema (1994) is an example of a LP model of an individual farm. Byrnes et.al. (1987) and Chavas and Aliber (1993) use mathematical programming to evaluate technical and economic efficiency of farm production. Dorward (1994) extends a simple LP formulation to apply in a semi-sequental framework with stochasticity. For a review of farm programming models including risk, one may look at a study by Hardaker et.al. (1991).

From time to time, the two alternative methodologies are compared in order to find a better one, and often votaries of one method only praise the benefits of their own choice. Bauer and Kasnacoglu (1989) however, emphasize the complementary nature of these two approaches: even if we take mathematical programming model as given, we can utilize econometrics to find parameters needed in the programming structure.

Positive mathematical programming (PMP), a technique introduced by Howitt (1995a, 1995b), delivers something between these two extremes. PMP utilizes a more flexible specification than the traditional linear programming models (Howitt 1995a). Like mathematical programming models in general, it is constructed on specific behavioural assumptions and restrictions. However, the model includes free parameters, which are used in fitting the mathematical model to observed data. The free calibration parameters are allowed to adjust in such a way that observed data can be exactly reproduced. Thus, by using the data, the normative character of mathematical modeling is weakened similar to an econometric approach. As Colman (1983) notes, econometric models often have strong normative elements as well, but these are tempered by the positive elements imparted by the data. Additionally, the technique reveals (asymmetric) information behind an agent's action by observing her behavior and assuming rationality. Paris and Howitt (1998) call the concept *revealed efficiency* as it resembles the revealed preference approach in consumer theory.

In a same time, PMP produces continuous, demand and supply functions, and is thus convenient for sensitivity analysis. Howitt (1995a) categorizes PMP models into primal and dual models. The first assumes a decreasing *yield function* and a constant *variable cost/acre function*, whereas the latter one assumes a constant *yield function* and an increasing *variable cost/acre* function. The choice of the approach depends on the data and the problem at hand.

PMP models allow more systematic validation compared to standard mathematical programming models. In their paper McCarl and Apland (1986) divide model validation into 1) validation by construct and 2) validation by results. In PMP modeling, validation by construct is done automatically, as that is an integral part of the first stage of a modeling sequence. The latter, validation by results, is done similarly as in econometric studies, using an out-of-sample data, although no statistical tests are available. As a result, PMP provides us with continuous (vs. stepwise) demand and supply functions as well as some additional information about farmers preferences (Paris 1994).

Howitt (1995a) uses a primal approach and a quadratic functional specification to present the PMP calibration method. In a companion paper, the author shows how the similar model can be built using a CES-specification (Howitt, 1995b). The two papers clarify some issues related to PMP modeling concept itself. The data requirements are the same as for a traditional linear programming model, however, depending on the functional specification, parameters for elasticities may be needed. Due to the flexability of the model and the relatively low data requirements, the approach has been used in large scale models by practicioneers, actually even before its official publication (Kasnakoglu and Bauer, 1988; Horner et.al., 1992; House 1987; Hatchett et.al., 1991). Academic applications include Rosen and Sexton (1993), which used PMP for modeling water markets, and Paris and Arfini (1995), analyzing regional agricultural policies, and Burke (1995) evaluating water markets in California.

PMP-modeling is a natural choice for analyses, which concentrate on revealing farm-type-specific or region-specific information or when the data set is plagued by large shocks due to significant institutional changes. In our case, we have a good data set available on Finnish book keeping farms, so the information contained in the data should not be overlooked, however, the production data contains a large institutional change due to a EU-membership and the subsequent change in the Finnish agricultural policy. Secondly, there is a need for a concise and versatile analytical tool, which, when well-defined, is so flexable, that diverse agricultural policy changes can be evaluated with the program.

### 3.3.2 Imperfect Data

Irrespective of the methodological choice, farm production decisions are often difficult to analyse due to data deficiencies. Commonly, at least three different problems can be noted: 1) only part of the farm level costs are observable and recorded in data sets, 2) the (cost) data available is often recorded in aggregates, not as output-specific-inputs e.g., fertilizer costs total per farm, and 3) often in econometric models the amount of data does not allow one to estimate the cross effects of different inputs in the cost function. In this section, we explain how the PMP-ME procedure can be utilized in order to overcome these shortcomings.

In mathematical models we commonly write farmers' profits as a function of input and output prices and amounts. However, besides observable marketable inputs with cash prices, there are also several unobservables in the production process. These unobservable nonlinearities and limitations affect farmer's behavior and thus costs. In an econometric model, these unobservable effects are left in the error term. In the PMP model, however, there is an implicit cost parameter, which can be interpreted as accounting for these limitations and nonlinearities producing hidden costs on the farm level.

*Hidden costs* are those non-market elements in the production system, which (non-linearly) affect farmers decision making and crop choice, but which are hidden from an outside observer. One example is land heterogeneity. Bellon and Taylor (1990, 1993), and Meng et.al. (1995) have hypothesized that at least in their studies, farm level land heterogeneity seem to be a key reason for farmers not fully specializing in one crop or crop variety. Other hidden, but very real farm level restrictions are farmers' time and financial and human capital endownments. These resources can be seen as additional reasons to reduce specialization. In Finland, where the growth period is very short and the "window of opportunity" for seeding and harvesting is narrow, a fixed time constraint during these crucial moments may be a significant reason for a land allocation.

In principle, a profit maximizing farmer allocates $j$ crops on $K$ plots of land, and uses $i$ inputs in the growing process. Using Bellon and Taylor's (1990) formulation, we can write an illustrative land allocation problem with two crops and $K$ plots of land as follows:

$$max\ \Pi = \sum_{k=1}^{K}[(\pi_{k1} - c_{k1})L_{k1} \quad + \quad (\pi_{k2} - c_{k2})L_{k2}] \tag{3.1}$$

$$s.t. \sum_{j=1}^{2} L_{kj} \leq \bar{L_k}.$$

The total profit from the farming activity is $\Pi$, $\pi_{kj}$ is revenue from the $j$:th activity in the $k$:th plot, and $\bar{L_k}$ is total amount of land of quality $k$. For simplicity, the costs are here assumed to be linear in plot size.

We can write the linear cost in more detail dividing the cost $c_{kj}$ into two parts: $c_{kj} = c^a_{kj} + c^h_{kj}$, the observable and the hidden cost respectively. Commonly, in economic analysis the first part, observable cost, is accounted for, but the second part, $c^h_{kj}$ is left without any attention due to lack of data. On the contrary, in this study Positive Mathematical Programming is used to reveal exactly this part. For the mechanics, see Howitt (1995a, 1995b). Assuming there is all necessary data available, PMP takes into account all the hidden cost, however, it does not reveal what is exact source of the cost, only its effect.

As mentioned above, there is another problem with the data, namely, we are often lacking some necessary information. It is typically the case that data on aggregate input useage are available but data on activity-specific inputs are not, because the latter are not recorded. For instance, Just et.al (1983) in their well known study name this *missing data problem* (the input allocations) to be one of the most difficult problems in estimating agricultural production functions. If we use the categorization of intensive and extensive margins[2], we can state, that commonly the information concerning extensive margin, like land area on each crop, is reported. On the other hand, input usage e.g., fertilizer use per crop, let alone, fertilizer use per each plot, is reported only in very special cases[3].

Even if the above problems are solved, still one more hurdle exists. Namely, in the multicrop production models, costs of all crops normally depend on each others i.e., there exist some *cross-effects in a cost function.* For instance, a higher level of capital may make fertilizer useage more productive. Similarly, at planting and harvesting time, farmer often chooses different crops and crop varieties, in order to stretch the time available for these tasks. Commonly however, insufficient data exist for us to estimate these cross effects, and then for lack of alternatives, these cross effects are often assumed to be either nonexistent or insignificant. Sometimes multiple crops are indexed to be a one unicrop, then these problems cease.

Some times also, alternative crops and crop varieties are estimated separately, independent of each other. This is the most common and the easiest way to do the evaluation and thus the most traditional way. Antle and Capalbo (1999) evaluate management decisions by single plots. In essence, the authors impose a separability between the plots, and thus e.g. interdependence of (quasi-)fixed factors cannot be included. For instance, the use of tractors and the farmer's management ability are overlooked. In general, production costs of alternative crops depend on other crops produced, and therefore, the costs should be evaluated interdependently. This is not normally possible, as there exist no data on cross-costs-effects for different crops. In

[2]Just and Antle (1990) and divide effects of agricultural policies into two: those affecting intensive margin i.e., input use on given crop on given plot and those affecting extensive margin i.e., land allocation decisions.

[3]This issue is studied by Leon et.al (1997) and Lence and Miller (1998a,b), which propose the ME approach. Lence and Miller (1998b) propose a use of generalized cross entropy, (CGE) for the case. See also Preckel (1998) and Lansink (1999).

mathematical terms, if the model for costs of two crops is written as follows:

$$c_1 = c_{11}x_1 + c_{12}x_2 \tag{3.2}$$

$$c_2 = c_{21}x_1 + c_{22}x_2, \tag{3.3}$$

where we do not have information on $c_{12}$ and on $c_{21}$. In this study, this lack of information is overcome, by relying on maximum entropy. Maximum entropy technique is included into a PMP routine in order to probabilistically define the cross-effect terms.

Summing up, in this study traditional mathematical programming analysis is extended to account for one case of non-existent market and for another case of non-existent data. Clearly, maximum entropy technique does not remove the need for better data. However, the technique allows one to extract all the information from scarce data in a scientific manner. Thus, it improves the analysis and broadens the possibilities, where mathematical programming may be applied.

## 3.4 The PMP-ME model

In this chapter, we develop the model. The model is a positive mathematical programming (PMP) model containing maximum entropy (ME) formulation as a part of it. The PMP approach is used here in order to circumvent problems due to ill-posed nature of the system. By adding constraints and a nonlinear calibrating function to the model specification the problem becomes manageable (Paris and Howitt, 1998, p. 130).

In principle, we construct the PMP-model in three stages. First, we build a linear programming (LP) model. Using base year data we constraint the LP-program to exactly reproduce the observed results. In the process, we obtain shadow values for constraints on the land allocation. In the second stage, we can use these shadow values in order to construct a cost matrix for a non-linear cost function, and thus to transform the linear program into a more realistic non-linear form. However, the shadow values gained from the LP-part allow us to analytically solve for only a diagonal, no-cross-effects matrix for the cost function. Here maximum entropy enrers into the picture.

The ME approach complements the PMP by enabling us to extract all the information from the data set, which is too scarce for traditional econometric methods. The ME methodolgy is used in order to reconstruct the otherwise diagonal cost matrix. The multiplicity-based ME procedure probabilistically finds the most appropiate cost matrix for the problem using the data and the marginal cost information from the LP-model (for more about maximum entropy, see Golan, Judge and Miller, 1996). The resulting cost matrix is a more realistic representation of the reality, as it reveals the cross-effects of different activities.

As a third step in the PMP, the non-linear program (NLP) is used to exactly reproduce the base period observations. The reproduction of the results allows us to recheck and evaluate the program formulation. By changing the program parameters, it may then be used for sensitivity analysis and policy simulations.

The model is a modification of the model presented in the article by Paris and Howitt (1998). However, due to a real-life panel data set in our study, the program had to be modified in order to account for multiple years and for zero observations (for instance, in some years a farmer $n$ cultivated e.g. rye, in some years she did not).

First, a cost matrix has been developed to account for multiple years i.e., for time series observations of each unit (in this report a unit equals to a farm or to a region depending on the case). A single, unit specific, cost matrix has been constructed to cover the whole time period.

Due to a multiple-year-data set, there are several cases where a unit has zero observations in some years. This causes a problem if we want to retain a "full potential menu" for each farmer for each year. In other words, we want to add a feature into the optimization procedure, that allows a farmer to choose from a broader selection of crops than what she that particular year had under cultivation. When designing such a procedure, we have to decide i) what crops a farmer should in general to be able to have in her menu (the same selection for each year), and ii) how to induce technical and economic information of each "zero-crop" into the optimization procedure.

Depending on the model version, we estimate the cost function either for a single farm or for a group of farms. To account for the zero observations, we estimate an expected production based on expected costs. As a result, our model may, in some cases, that suggest a farmer to grow crops which she did not grow that particular year. However, by the construction the model does not suggests a farmer to grow a crop which was never grown on that particular farm.

### 3.4.1 Mathematical Programming with Calibration

Traditionally production used to be modeled in primal formulations maximizing total net revenue of production. Oftentimes, dual formulation minimizing the costs, given a particular amount of production is more fruitful approach and reveals more information about the production process. In the primal formulation, costs of production are commonly difficult if not impossible to observe. Even if data exists on some input costs, there are many unobservable non-market costs present affecting production costs. A remedy is to use quantities of the primal formulation in order to find dual costs. One may use primal quantities to perfectly map the dual costs and thus learn more about the production process, and of the costs of production. In our case, the duality helps us to operationalize the PMP-system.

When applying the PMP technique, the problem is first written in a simple primal LP formulation maximizing total revenue:

$$Max\ TR = p'y \tag{3.4}$$

$$s.t.\ Ax \leq B \tag{3.5}$$

$$x \leq \bar{x}_R + e \quad (3.6)$$
$$x \geq 0. \quad (3.7)$$

where the activities of the LP model are artificially constrained to produce exactly the results observed. Observed quantities are written as $\bar{x}_R$. The dual of the same program is:

$$Min\ TC = B'w + \lambda'\bar{x}_R \quad (3.8)$$
$$s.t.\ A'w + \lambda \geq p \quad (3.9)$$
$$\lambda \geq 0, w \geq 0, \quad (3.10)$$

where $W$, and $\lambda$ are duals of (5) and (6).

The shadow values of the calibration constraints can be utilized to develop the model further. A primal of the optimization problem using a quadratic functional form maximizing the total *net* revenue appears now as follows:

$$Max\ TNR = p'y - 0.5 * x'Qx \quad (3.11)$$
$$s.t.\ Ax \leq B \quad (3.12)$$
$$x \geq 0, \quad (3.13)$$

where TNR is the total net revenue and $Q$ is a positive semidefinite matrix.

In the second stage, we reconstruct the non-linear cost matrix $Q$. To proceed we write the dual of the program where we minimize the total cost:

$$Min\ TC = B'w + 0.5 * x'Qx \quad (3.14)$$
$$s.t. A'w + Qx \geq p \quad (3.15)$$
$$x \geq 0, w \geq 0. \quad (3.16)$$

As shown e.g. in Paris (1994) and Paris and Arfini (1995)[4], if we define $\lambda = Qx$, the above dual formulation of the PMP program equals to the dual of an LP program maximizing the total revenue $p'y$ with similar constraints added with the *calibration constraints* $x \leq \bar{x}_R$. The variable cost functions can be written $\lambda'\bar{x}_R = 0.5 * \bar{x}'_R Q \bar{x}_R$ for LP and PMP programs respectively. In order to utilize the model an estimate for $Q$ must be recovered. This is achieved by solving the LP program and using the resulting shadow values, $\lambda's$, and observed quantity realizations, $\bar{x}_R$, to construct the cost matrix, $Q$.

As noted in Paris and Arfini (1995) such a mechanical procedure utilizing a single observation allows one to only generate a diagonal matrix. However, in reality there are generally cross-effects between different activities, and thus diagonal cost matrix is not an appropriate representation of reality. The maximum entropy method must be used to recover the cross-effects of alternative activities in the cost function

[4]The authors call this formulation PQP, a positive quadratic programming, and note it to be a special case of the PMP. Here we do not differenciate between the different functional forms.

### 3.4.2 Recovery of the Cross-Effects using Maximum Entropy

Maximum entropy is a method for recovering an unkown probability distribution from given moment constraints. ME method was developed by Jaynes (1957a,b) using Shannon's (1948) definition of entropy as an information measure (See an appendix I). If there is a system of equations, with less constraints (observations, equations) than unknowns (probabilities) to be discovered, the system has several solutions. For such a case, the least informative solution from a feasible set can be found, using Jaynes' ME-method.

Jaynes' entropy is a measure of information. It is based on multiplicity. The measure is maximized, when there is the weakest set of assumptions (exogeneous structure) consistent with the observed data and with the stated model[5]. The intuitive meaning behind the entropy measure is, according to Jaynes, that the entropy measure equals to "amount of uncertainty" of a probability distribution, which is maximized, subject to constraints. This in turn forces the system to use all and only information what it has of the system, no more and no less.

As in Paris and Howitt (1998) the marginal cost values from the LP part and the observed data $\bar{x}_R$ are used in order to determine values, which produced the diagonal cost matrix appearing in the LP part. Using the Cholesky factorization we may write the matrix $Q = LDL$, where $L$ is a unit lower triangular matrix and $D$ is a diagonal matrix. If $D > 0$ then the Cholesky factorization guarantees the recovered matrix to be both positive definite and symmetric as required.

The matrix notation results in the following system:

$$\begin{bmatrix} L_{11} & 0 & 0 \\ L_{21} & L_{22} & 0 \\ . & . & L_{j,j'} \end{bmatrix} \begin{bmatrix} D_{11} & 0 & 0 \\ 0 & D_{22} & 0 \\ 0 & 0 & D_{jj'} \end{bmatrix} \begin{bmatrix} L_{11} & L_{12} & . \\ 0 & L_{22} & . \\ 0 & 0 & L_{j',j} \end{bmatrix} \equiv \begin{bmatrix} Q_{11} & Q_{12} & . \\ Q_{21} & Q_{22} & . \\ . & . & Q_{j,j'} \end{bmatrix} \tag{3.18}$$

In the context of the ME, we may think of each element of the $L$ and $D$ matrices as an expected value of an associated probability distribution defined over a set of known discrete support values (GJM). In other words, we can write the each element of the $L$ and $D$ matrices as a sum function of discrete support values $Z_L, Z_D$ and respective probabilities $P_L, P_D$:

$$L_{jj'} = \Sigma_k Z_L(j,j',k) P_L(j,j',k); j,j' = 1,...,J \tag{3.19}$$

$$D_{jj'} = \Sigma_k Z_D(j,j',k) P_D(j,j',k); k = 1,...,K. \tag{3.20}$$

[5]The entropy measure can be written as follows:

$$H(p) \equiv -\Sigma_{n=1}^{N} p_n ln(p_n) \equiv -p' ln(p), \tag{3.17}$$

where $p' \equiv [p_1, p_2, ..., p_N]$ is a discrete probability distribution. The purpose is to find the probabilities $p_N$, which maximize $H$, with respect to constraints, which can be thought of being a set of observations.

As written out above, the main purpose of the ME is to find for the each element of the $L_{jj'}$ and $D_{jj'}$ matrices the probabilities $P_L(j, j', k)$ and $P_D(j, j', k)$, that maximize the entropy function $H(\,)$ subject to constraints. In other words, one has to determine the most likely values, $(P_D, P_L)$ which, together with the given supports, produced the diagonal cost matrix appearing in the LP part. For our case, the problem is written out explicitly below:

$$
\begin{aligned}
max_{P_L,P_D} H(P_L, P_D) \equiv & - \Sigma_{j,j',k} P_L(j, j', k) ln[P_L(j, j', k)] && (3.21)\\
& - \Sigma_{j,j',k} P_D(j, j', k) ln[P_D(j, j', k)] && (3.22)\\
s.t.\ Qx_R = & \ LDL'x_R = (Z_L P_L)(Z_D P_D)(Z_L P_L)' x_R && (3.23)\\
\Sigma_k P_L(j, j', k) = & \ 1\ ;\ \ j, j' = 1, ..., J && (3.24)\\
\Sigma_k P_D(j, j', k) = & \ 1\ ;\ \ j, j' = 1, ..., J. && (3.25)
\end{aligned}
$$

Here the first constraint is from the set of observations and the two other constraints are the adding up constraints of probabilities.

The objective function reflects the amount of our information on values of the elements of $L_{j,j'}$ and $D_{j,j'}$. The less information about the parameters we have, the closer the system is to a uniform distribution. The data constraint brings more information into the system and thus pushes the system further away from the uniform distribution. Another way to look at the problem is that by maximizing the above system with respect to the variables, the system is forced to resemble the uniform distribution as closely as possible, still satisfying the constraints. After that, the third and the last step in the PMP procedure follows.

## 3.5 Empirical Estimation

In the empirical part, our aim is to evaluate the performance of the modeling approach. So far we have constructed a model applicable to a small number of farms or even to a single farm. Now, we proceed by evaluating the performance and the significance of the single-farm model. This is done by comparing observed land allocations to predicted land allocations resulting from two alternative model versions: *i)* individual cost function model (ICM), and *ii)* common cost function model (CCM). In the CCM we estimate one common cost function over all farms in that sample, whereas in the ICM we estimate an individual cost function for each farm. The main question is, do we get an improved out-of-sample forecast by using the individual cost function model.

### 3.5.1 The Empirical Model

Mechanically, the LP-program is easily solved in a single optimization for all farms together. Following the LP, the cost matrix estimation is reconstructed using the ME procedure. In the ICM, a farm-specific cost matrix is estimated for each farm to be used over all time periods. In the CCM, one common cost matrix is estimated to be used for all farms over all time periods in the sample. To ease the mechanical calculations in the ICM, each farm is estimated separately individually looping over time periods.

In the third part, the ME-estimated cost functions are used to calibrate the model to the base period(s) data and later to forecast out-of-sample. The optimization procedure is run in loops, one year at the time looping over individual farms. After the solutions, certain statistics are calculated to evaluate the results. First, farm specific differences in observed land allocations and model results are calculated. This reflects the model fit by a farm. After that we evaluate the annual average differences by a crop as this may be a more valued statistic for a policy maker, when the model is used for actual policy analysis. Eventually, we calculate mean values over all farms and periods.

The model testing is done in three stages: i) we test the proper functioning of the model, ii) we test the calibration fit of the ICM and of the CCM in order to find the preferred program, and iii) we test the significance of the cost function estimation by evaluating the out-of-sample forecasts produced with the two alternative versions. The main concern is to measure the policy impact at the extensive margin (cropping pattern, land allocation). The intensive margin (input use e.g, chemical use) is put aside at this point.

For a PMP land allocation study we need all the general variables and parameters which affect farmers annual decision making[6]. PMP is especially good for forecasting short term, or "instant" adjustment. An annual land allocation decision is a good example of this; where a farmer concentrates mainly on relative prices of inputs and outputs when deciding what to cultivate. If a new crop requires significant adjustments in physical or human capital, we can expect the farmer to invest time and money on these productive factors over a longer period of time. In this way, the human capital and physical capital can be seen as factors limiting the set of available crops rather than affecting their production directly.

Naturally, PMP model may be done recursively in order to learn more about longer term adjustments. In this study, the one-year-cycle of production is emphasized as only (annual) crop farming is analyzed. Generally, perennial agricultural crops are not cultivated in Finland, except grasses commonly produced for livestock. However, the many other fixed factors present in livestock production can be omitted in the model as the sample consists only of crop farms.

[6] In this study, we assume away rigidities, like crop rotation, or specialized machinery, which cause years to be interdependent.

### 3.5.2 The Data

The farms investigated here are sampled from the Finnish book keeping farm data collection system. The system has worked since 1920's. Since 1995, after Finland joined the European Union, the book keeping system has been a part of a EU agricultural data collection, so called FADN-data system. Currently, there are about one thousand farms in the system.

The Finnish book keeping data is not a randomly sampled data set. Most of the farms have been part of the system for several years. Two farms have been part of the system since its beginning. As a result, the book keeping system gives a alightly biased view of the reality. The farms in the group tend to be larger, and more profitable than Finnish farms in general. Similarly, the farmers themselves tend more often to be full-time farmers. The data set is very appealing as it allows one to create (panel) data sets, which have the same exact farms in a panel for several years.

Crop farms[7] with continuous observations over the years 1989-97 were chosen from the book keeping data. Furthermore, the sample was narrowed to cover only the farms concentrating on small grains. Although, there are crop farms located everywhere in Finland, for climatic reasons, they tend to be concentrated in southern and western parts of the country. A location of the farms appears through zones (see the figure 3.2). The A-zone is the southernmost zone, the B-zone covers the area directly north, and the rest of the farms are in generic C-zone. The division resembles the practice used for agricultural subsidy payments.

The crops produced are rye, wheat, barley, oats, oilseed, sugarbeet and miscellaneous. The production data covers the years of 1989-1997. In the southern part of the country the most common crops are wheat, rye and barley, whereas in the northern part barley and oats are the most common cereals grown. During the period, only three farms out of the total of 36 cultivated sugarbeet. The miscellaneous crop group cover e.g hayseed, potatoes and peas, however, miscellaneous crops comprise a very small part of the total area cultivated. The field area is measured in hectars.

Inputs are divided into six categories: land, labor, machinery, fertilizers, chemicals and the other. Land allocation is measured by hectars and for cost of land we use a proxy of 1000 Fim/ha. For other categories we use the cost amounts in the data. The "other" costs cover several types of payments for instance, crop drying.

Before doing the PMP analysis, the aggregated input cost had to be decomposed to output-specific input costs. Here model profitability calculations were used, prepared by an extension service (MKL, 1992). Fertilizer and chemical costs were taken as given. The machinery cost consists of tractor, harvester and post harvest drying costs. The labor cost is taken to be the sum of tractor and harvester hours added by 20 percent and valued 30 Fim per hour. The seed cost and firm capital costs make up the rest of the costs called "other" in the data set. The values can be found from

[7]Here the farms are called crop farms when over fifty present of their revenues come from crop farming.

a publication by an extension service (MKL, 1992).

As a reality check, a few farmers were also questioned about their farming costs. The subjective information collected from the farmers suggested, that in farmers' own calculations labor and fertilizer costs are less important and machinery costs more important than in the model calculations. However, this may be partly due to what was included into value of machinery hours. The money-costs per hectars were close the same in both calculations, which was reassuring.

For convenience the yields are scaled to tons. To simplify the system, we do not allow negative revenues from production of any crops. In essence, this means that rotational crops producing negative crop returns and catastrophic years with negative economic crop returns are smoothed over. This is done by scaling down the costs unilaterally. In practtice, this means that we will still find the correct land allocations and relative changes, but we will not be able to determine accurate levels of returns and profits.

The data at hand cover several farms in diverse natural condition over 6(9) years. Most of these farms only cultivate 1-3 crops ("a main staple"), which are grown practically every year. Commonly farms have other 1-2 crops, which are cultivated occasionally or only few years during this period. In other words, we have some zero observations in the data. To avoid potential problems in the individual cost function models, we use expected values for the cost and yield parameters when needed.

For the LP-part, linear costs are used and the quantities are multiplied by price. The prices are calculated such that they include direct subsidies as part of them. This is particularly significant in the years after the EU-membership as in those years direct subsidies play such an important role in farmers income.

## 3.6 Results

In the text above we have explained the structure of the model, and in this section, we evaluate the empirical performance of the model. In the empirical evaluation we have four specific goals we want to clarify: *i)* does the model calibrate as supposed, *ii)* does the model with more detailed information produce a better calibration fit, *iii)*, is the model affected by a region, and *iv)* does the model with more detailed information produce a better fit when forecasting out-of-sample.

Two different versions of the empirical model are constructed. A baseline model is called an individual-cost model (ICM). In this version, the cost function for the each farm in the sample is estimated separately. A hypothesis is, that as the baseline version uses the most detailed information, it will produce the closest fit in the calibration and in the forecast. The second version of the model is called a common-cost model (CCM), because a common cost function is estimated for all the farms in the sample. Additionally, a simulation model (ISM, CSM) is constructed to test the out-of-sample model behavior and to forecast.

The models (ICM, CCM) are fitted to data for the years 1989-1994. The calibration fit is then evaluated in order to see if the fit is significantly different between the models. Then the respective simulation models (ISM, CSM) are used for out-of-sample forecasting for the years 1995-1997. The forecast results are compared to observed data in order to evaluate the cabability of the model to forecast changes to agricultural land use and the significance of modeling cost functions individually.

The models are applied to the data set as a whole and also separately to three different regional zones, A, B, C, in turn. The variable of interest is land allocations of different crops. The total amount of production is not included in the evaluation, as the stochasticity and e.g. annual climatic variation affect the yields considerably. The comparison is based on a *difference-per-farm -measure (dpf)*. This measure is calculated simply by taking the difference between the observed land allocation and the model prediction. Furthermore, an annual *average dpf (adpf)* for each year (over all farms), and a *mean dpf (mdpf)* for the each farm (over all years) are calculated. Finally, a *mean average dpf (madpf)* over the all farms and years simultaneously is found. Respective measures are then created for observed *production variation (pv, apv, mpv, and mapv)* in order to evaluate the variation inherent in the data set.

### 3.6.1 Pre-testing of the Model

All the three versions are first tested in order to ensure they properly work. The baseline model is tested by observing its calibration fit from single-year runs. By the construction, the ICM estimates an individual cost function for each farm, and therefore the single-year forecast should produce a perfect fit for the each year. In other words, the model can be exactly calibrated to single years and it can be also calibrated to several years with an error term. The test showed that in the case of single-year data, the ICM indeed produces the perfect fit, and thus the version works. For multi-year data, the fit would never be exact, as in this case the cost function is estimated over several periods. The CCM version estimates the cost function simultaneously over all farms and over all years. Therefore, the version can be tested only by observing a single-year - single-farm calibration fit. For the CCM this fit should be exact, and according to our random tests, this is the case.

Additionally, the ICM is tested with a simple policy change. In this simple sensitivity analysis the price of wheat on the A-zone was gradually increased. The model worked as expected producing gradually increasing wheat area and eventually driving most of the other crops out of production.

The simulation models are tested by first running the ICM for a single year data producing the cost information for that year. In the second stage, single-year simulation model (SM) is run with this cost information and the resulting fit should again be perfect. This indeed is the case here. In all the cases, the calibration fit was within one percent, thus we can conclude that all the versions work properly.

### 3.6.2 Evaluation of Regional Effects

The regional effects apparent in the data are taken into account by dividing the data set into three based on the subsidy zone where the farm is located. First, the model predictions are compared to observations and to observed product variation in the data set. The regional (i.e. zone) effect evaluation is done using the baseline model, ICM alone.

For instance on the zone A, for rye, wheat and sugarbeet, the ICM predicts the allocation quite well and produces smaller *madpf's* compared to production variation, *mapv*, calculated from the data. On the other hand, for barley, oats and oilseed, the model seems to produce larger difference than the variation in the data. The annual observed production variation is the clearest in rye ($apv$ = 12-173 %), whereas the barley growing is quite stable and production variation small ($apv$ = 24-31 %). Sugarbeet is only grown on three sample farms in the A-zone, so for that part the discussion only applies to the zone A.

In the B zone, ICM predictions (*adpf's*) are clearly smaller than observed production variation (*apv's*) only in rye production. For wheat and barley, the prediction differences are also commonly smaller than the observed variation, although, there are some exceptions. When the observed variation, *apv*, is compared to *adpf's*, it is commonly much higher in the B-zone for rye, wheat and oilseed production. In turn, the observed variation, *apv*, in barley and oats production is smaller than *adpf's*. This may signal the popularity of the crop in the region: on the B-zone, rye and wheat are more exotic due to their added riskiness compared to the more common, barley and oat crops.

The farms in the zone C behave in a similar vein as those in the zone B: the main crops, barley and oats, normally have larger prediction errors (*adpf's*) than observed variation (*apv's*). For other crops results vary. In the end, taking all the farms together the above differences average out. The apv's are commonly smaller than adpf's for barley, oats and oilseed, which are the stable, main crops in the whole country scale. Thus the results from the individual regions are reinforced.

The small size of the *apv's* seems reflect the popularity (production stability) of the crop on a particular zone. The particular crop may not have the largest land allocation in a zone, but the high *apv*-value signals that crop to be "the main staple" in the region. It is a crop that is grown from year to year in the area possibly as it is well-suited to local climate and growth conditions, has a low risk and relatively reasonable returns. On the other hand, highly varying *apv's* may signal some wildly varying agricultural policy measures. For instance, subsidies (and thus prices) in rye production used to vary considerably before the EU-era, and thus they may have caused some changes in the rye production area and thus in the *apv's* for rye.

Small *adpf*-values show that the model is able to capture the important issues in farmers' decision making. They tell us that the model clearly reflects the actions of farmers growing those crops. In turn, the crops with higher *adpf's* have some other, important motives behind their growing decisions besides those included in the model. As a whole, if predictions are reasonably good, we can assume that the model takes into account the important issues behind growing of the particular crop. In turn, weak predictions suggest that the model overlooks some features in production: *i)* maybe the crop is only "an additional crop" (vs. main stable) in that particular area, *ii)* maybe there are ad-hoc policies affecting the profitability of that crop and changing from time to time (e.g. rye in Finland), or *iii)* maybe there are some hidden connections between that particular crop production and the production process (animal production, waste management, rotation, etc.). In any case, the relation between the observed variation and the predictions are not systematically connected, as there are several factors besides those included in the model, which may affect farmers'decision making. Only the effect of price is fully included in the model.

### 3.6.3 Evaluation of the Calibration Fit

After the regional comparison, the ICM and CCM versions are compared in order to find the differences due to the cost function estimation itself. A priori, the individual cost function is assumed to produce a better fit in the calibration compared to the common cost function model. The evaluation is based on the aforementioned *dpf*-measure. The *dpf's* are calculated for the each zone and for all the farms together.

For the each farm the *mdpf* reflects how well the model predicts the land allocation over the base years 1989-1994 i.e., how well the model is suited for the particular farm. For the comparison the medians of the *mdpf's* were observed, as the median is less sensitive for possible outliers. The main conclusion is, that for all the zones and for all the crops, the *mdpf's* are lower for the ICM, and thus our prior expectation about the preferability of the ICM is supported by the test. Below we present a ratio of the *mdpf*-measures for the CCM and ICM i.e. $mdpf(CCM)/mdpf(ICM)$. When the ratio is close to unity, the alternative versions predict as well. The higher the ratio is, the (relatively) better the ICM version is. If the ratio is below one, the CCM is the better predictor. A similar comparison was done using the *adpf's*, which reflect how well the prediction works in a particular year. The results (in table 3.2) were quite similar except for rye in the zone C. This is the only case where the ICM seems to produce weaker results than the CCM. This may be due to the smallness of the area in question, or due to some other numerical detail. However, in general the ICM produced better predictions than the CCM.In the figure 3.3 the numerical values of the *median adpf's* are listed to give a feel to a reader, how far from the observed value the predictions lay. In many occacions the predictions were quite far off the observations. In order to see the differences that usage of a median and a mean may cause in evaluation of the models, the means of the *adpf's* were also calculated and are listed below (figure 3.4). For this particular case the difference is not significant, the only qualitative difference is the size of the means for the oats in A-zone. This is due

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-zone | 1.57 | 2.2 | 1.83 | 1 | 1.83 | 1.92 |
| B-zone | 1.27 | 1 | 2.22 | 1.92 | 2.03 | |
| C-zone | 1 | 2.54 | 2.22 | 1.18 | 1.35 | |
| All farms | 1.27 | 1.65 | 2.36 | 1.59 | 1.88 | 1.93 |

Table 3.1: The ratio of the medians of the mdpf's (mean dpf's for each farm) in the calibration.

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-zone | 1.67 | 1.25 | 2.29 | 1.56 | 1.74 | 2.25 |
| B-zone | 1.69 | 2.14 | 4.73 | 3.14 | 2.31 | |
| C-zone | 0.92 | 2.79 | 2.74 | 1.42 | 1.74 | |
| All farms | 1.44 | 1.44 | 2.38 | 2.38 | 1.89 | 2.13 |

Table 3.2: The ratio of the medians of the *adpf's* (average dpf's for each year) in the calibration.

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-ICM | 51% | 20% | 35% | 32% | 47% | 12% |
| A-CCM | 85% | 25% | 80% | 50% | 82% | 27% |
| B-ICM | 59% | 58% | 15% | 22% | 42% | |
| B-CCM | 100% | 124% | 71% | 69% | 97% | |
| C-ICM | 100% | 29% | 23% | 33% | 43% | |
| C-CCM | 92% | 81% | 63% | 47% | 75% | |
| W-ICM | 62% | 34% | 26% | 34% | 47% | 16% |
| W-CCM | 89% | 49% | 62% | 81% | 89% | 34% |

Table 3.3: The medians of the *adpf's*.

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-ICM | 48% | 22% | 42% | 71% | 48% | 14% |
| A-CCM | 74% | 38% | 87% | 61% | 84% | 27% |
| B-ICM | 46% | 70% | 32% | 28% | 55% | |
| B-CCM | 67% | 127% | 95% | 65% | 96% | |
| C-ICM | 66% | 24% | 24% | 39% | 45% | |
| C-CCM | 59% | 54% | 61% | 51% | 77% | |
| W-ICM | 56% | 32% | 35% | 44% | 50% | 15% |
| W-CCM | 84% | 65% | 72% | 76% | 87% | 35% |

Table 3.4: The mean average differences, *madpf.*

to a large error in the predicted oats allocation at that particular point, and since the median measure is not significantly affected by the outlier a difference occurs.Based on the indicators, we can conclude that the ICM calibrates better, producing a closer fit than the CCM. This follows our prior expectation, that the more detailed model is capable of using available information more efficiently and thus is preferable as an estimation procedure. It also shows that there is heterogeniety among farms in a region.

### 3.6.4 Regional Significance of the Cost Function Estimation

The PMP-ME model studied here is an application-minded model designed to be used for practical analysis. Therefore, we are interested in how well such a model works in practice. The calibration test in the previous section only reassures a reader that the more detailed model produces better results as it should. However, one does not know how much better the results are i.e., are they significantly better, and worth the cost of added complexity. In this stage, we will proceed by testing how significant differencences the two aforementioned versions of the model, ICM and CCM, produce in practice, when they are used to forecast the land allocation out-of-sample.

In the calibration procedure six years (1989-1994) from the sample data were used to reconstruct the cost function and three years (1995-1997) were saved for out-of-sample model testing. The reconstructed cost functions were utilized in the simulation models ISM (individual-simulation model) and CSM (common-simulation model) for forecasting the land allocations. The simulation results are now evaluated similarly as the calibration results above.

Generally, several things affect forecasts and forecasting performance. The model construction itself naturally rules what is included in and what is excluded from the model. For instance, overlooking adjustment costs i.e., the assumption of instant

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-ISM | 37% | 38% | 41% | 126% | 60% | 17% |
| A-CSM | 75% | 19% | 51% | 67% | 100% | 5% |
| B-ISM | 33% | 60% | 19% | 29% | 109% | |
| B-CSM | 33% | 72% | 29% | 37% | 100% | |
| C-ISM | 39% | 17% | 23% | 78% | | |
| C-CSM | 50% | 21% | 48% | 100% | | |
| W-ISM | 33% | 38% | 24% | 32% | 65% | 17% |
| W-CSM | 62% | 23% | 44% | 39% | 100% | 14% |

Table 3.5: The medians of the mdpf's (mean dpf's for each farm) in the simulation 1995-1997.

adjustment causes weak forecast performance when policy environment and policy measures are rapidly changing (e.g. the Finnish EU membership). In general, high variation in crop allocation affects the performance i.e., if there are not strong regional favorites grown from year to year, the forecasting is difficult.

In practice, the PMP-ME model at hand can be used to forecast year-to-year land allocation due to policy and price changes. Commonly, one particular farm is not an interest, but rather the changes on an aggregate level are more important. In the evaluation process we are then especially interested in how well the model forecasts annual land allocation decisions on aggregate or on average, and thus the main interest is on the measure of *adpf's* and on the *madpf's*.

In general, for the A-zone, the annual observed variation in land allocations is the smallest for wheat, about 10 %, and it is quite reasonable for barley also, about 28 %. The variation in sugarbeet is also less than 20 %, however, sugarbeet has only been grown on three farms. When comparing the forecasts to observations, the forecast performance varied between the ISM and CSM versions, neither one was clearly better than the other.In the B-zone, the ISM version generally produced better results. Only in the case of oilseed production in 1996 and in 1997 were the CSM results closer to observed results due to some outliers. The annual observed variation was the least for wheat and barley, 10 % and 16 % respectively. Also oats and oilseed allocations varied only about 20 % percent on average yearly. The best forecast performance was produced for barley and oats, which overal had an average error 27 % and 31 % respectively. In this case the ISM was clearly better for barley and oats, and only in the case of oilseed the CSM performed better.

The annual observed variation in the C-zone seems to reflect the smaller number of crops available (climatological reasons) to farmers as already noticed in the B-zone. The annual variation measure was on average only 14 %, 20 % and 12 % for barley,

| | rye | heat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-zone | 2.03 | 0.5 | 1.24 | 0.53 | 1.67 | 0.29 |
| B-zone | 1 | 1.2 | 1.53 | 1.28 | 0.92 | |
| C-zone | 1.28 | 1.24 | 2.09 | 1.28 | | |
| All farms | 1.88 | 0.61 | 1.83 | 1.22 | 1.54 | 0.82 |

Table 3.6: The ratio of the medians of the *mdpf's* in the simulation 1995-1997.

oats and oilseed respectively. The simulation seems to also fit quite well. The ISM forecast for barley and oats performed quite well with reasonable error of 17 % and 31 % respectively. The success in oilseed forecasting using the ISM was not as good, due to some large outliers in the year 1997. In general, the ISM produced clearly better forecast in the C-zone except in the case of oilseed production. In table 3.6 the differences are written out as ratios of the alternative versions.After evaluating the three zones separately, the forecasts were evaluated for the all farms together. The annual observed variation in total was the smallest for wheat (11%) and barley (21%), and for the oats and oilseed the variation was also less than 30%. Only the rye allocation seems to vary wildly. In the case of all farms together, the alternative versions cannot be clearly ranked. In some cases the CSM seemed to work better, whereas in the case of rye, and especially in the case of barley, the more detailed model produced clearly better forecasts. If the ratios for the calibration and for the forecasting are compared, one notices that most of the ratios are clearly reduced. Whereas the calibration produced a much better fit in the case of ICM, the difference is much less in the case of the forecasts. In other words, with this data, the more detailed model does not seem to offer us significant value added in forecasting.

The mean of the annual forecasts were calculated next (see the table 3.7). A comparison of these values to calibration values shows, that the forecasting with the model is not very accurate in our case. The differences in many cases are over 50 %, even over 100 % in some cases. Thus, more work has to be done, in connecting the models and data together for the purpose of forecasting.The ISM seems to perform clearly better in the B-zone and the C-zone compared to the A-zone and to the forecasting of the all farms in one group. This could be due to two reasons. First, the ISM is designed for the cases with few farms and little information. When there is a large sample and ample information available, there are other, more suitable data intensive methods methods (e.g. econometric methods) to be used for evaluation and forecasting of farm(ers) behavior. In the case of a larger data set, the data may possess such an amount of information, that the combining the farms together produces better results than taking into account the detailed farm-specific information. The PMP-ME is exactly the tool to be used when all the available information has to be extracted

| | rye | wheat | barley | oats | oilseed | sugarbeet |
|---|---|---|---|---|---|---|
| A-ISM | 90% | 38% | 57% | 282% | 86% | 32% |
| A-CSM | 77% | 20% | 71% | 112% | 94% | 12% |
| B-ISM | 83% | 60% | 27% | 31% | 117% | |
| B-CSM | 100% | 72% | 64% | 55% | 100% | |
| C-ISM | 78% | 17% | 31% | 86% | | |
| C-CSM | 100% | 28% | 49% | 77% | | |
| W-ISM | 85% | 41% | 39% | 108% | 94% | 34% |
| W-CSM | 98% | 34% | 64% | 62% | 98% | 34% |

Table 3.7: The *madpf* in the simulation 1995-1997.

from a minimum amount of information, and thus it works relatively better in such limited information cases. Second, in the case of the B-zone and the C-zone, the "crop menu" available for farmers is cearly smaller than in the A-zone, which may affect the performance. When a farmer mostly cultivates only 2-3 crops, a farm-specific model may work better and produce better forecasting results. In turn, in the case where a farm may choose from several available crops, and always pick the most appealing alternative for that particular year, a CSM may give more structure to the model and thus produce a better forecast.

The above discussion and the diagnostics used allows us to compare the alternative model versions. The comparison is clearly not exlusive. First, the calibration process fits the model only on average over several years, thus, a perfect fit is not expected. Secondly, the model only includes price incentives, leaving out e.g. rotational aspects, adjustment costs, etc. Therefore, we should not expect the model to exactly reproduce the calibration years, neither to perfectly forecast out-of-sample. More exact diagnostics should be developed in order to compare the results A diagnostic taking into account the annual observed variation in a systematic manner should be developed in the future. In our models, there currently are not a clear ways to include/exclude the annual observed variation in the performance testing. If it was assumed, that the model totally reproduces the farmers' decision making process, the annual observed variation should be internalized in the performance evaluation. Similarly, a larger sample in both, number of farms, and number of years should be studied later in order to improve the comparison.

## 3.7 Summation and Further Studies

Farm level optimization models have a wide useage in today's agricultural economic research and policy making. The results from production unit models may be used as inputs in the regional model, or in sector level simulation studies as well as in computable general equilibrium models. These models allow construction of so called micro-simulation systems, where agricultural policies have concrete, realistic effects on farms, and these effects are then consistently carried through and aggregated on the sector level. This in turn allows an investigation of new policies on different types of farms and also their micro level socio-economic effets.

Positive Mathematical Programming complemented with Maximum Entropy estimation, the approach used in this study, can now be used instead of traditional linear programming models. Due to its minimal data requirements, PMP-ME may be used in majority of the cases, where econometric approach proves handicapped and where LP models were used earlier. The clear benefits from PMP-ME approach are 1) more realistic cropping patterns, 2) continuous supply functions and thus clearer comparative statics as well as 3) more efficient utilization of both data and theory.

The PMP-ME model used in this study is a flexible model, which can take into account detailed farm level agricultural policies. It allows individually modelling of farms, when needed. With the model at hand, we are able to use our detailed data set for forecasting of land allocation. When required, the model also allows sensitivity analysis and policy simulations. The model can be exactly calibrated to single year data. It can also be calibrated to a multiple-year data set with an error term.

Two versions of the model were run and compared to each other. In the baseline model (ICM), an individual cost function is estimated for each farm in a sample, covering the calibration period 1989-1994. For a comparison, an alternative version (CCM) is evaluated, where a common cost function is estimated for all farms in a sample, covering again the same calibration period. As expected, the individual cost function model produces a better calibration fit. The ICM reproduces observed land allocations with fewer errors compared to CCM. This reassures us that a more detailed modeling produces a better base year prediction.

The same two model versions are further compared in a simulation test. In the test, the model versions are used to forecast farmer land allocations in an out-of-sample period 1995-1997. In this case, we cannot find clearly better model. For some crops and years, the ICM performs better, and for others the CCM works better. The ICM seems to have an advantage in case of small number of farms and when the crop menu available for a farmer is smaller. However, when there is a larger data set available, individual cost function modeling does not seem to be as beneficial.

The basic model has been developed, and can now be used for simple policy simulations and forecasting. However, more work is required in testing it and in trying to make it more compatible with the Finnish book keeping data. Also the model performance can be evaluated in the context of a more aggregated data set i.e., with a country level data.

In the future, the model can be extended in many dimensions. The livestock production can be added to a model. Especially, the introduction of beef and milk production will bring more structure and endogenous constraints into the model land use. Another, related extension is an addition of dynamic effects into the model. Carry-over effects can be included through e.g. a crop rotation, or a storage possibility. Similarly, environmental issues may be included into the model e.g. by adding in a nutrient balance module. New "crops" or new production enterprices can be introduced into the model by adding in a possibility of a public good production as an alternative commercial activity. For instance, a farmer may agree with a government to decrease use of pollutive inputs or to use low-$CO_2$ emitting production methods in farming.

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## 3.9 Appendix I: Maximum Entropy Mechanics

Maximum entropy (ME) is a method for recovering and processing information when the underlying sampling model is incompletely or incorrectly known and the data are limited, partial or incomplete. This is how Golan, Judge and Miller (GJM) describe the use of maximum entropy in the beginning of their book (1996). ME was discovered by Shannon (1948) and further developed by Jaynes (1957). After being used for 30-40 years in engineering, ME was introduced to wide audience of applied economists in the middle of this century. Since the introduction, ME has been been utilized in several applied studies, see e.g., Golan, Judge and Karp (1996), Golan, Judge and Perloff (1996), Leon et.al. (1997), Paris and Howitt (1998), and Miller and Plantinga (1999) Fernandez (1997), Kaplan (1999). Besides the applied studies, work has also continued on characterizing the solutions and evaluating the stability of results (Lence and Miller, 1998a; 1998b).

In the cases, where data is plagued by aforementioned limitations, a problem is often said to be ill-posed and/or ill-conditioned. The problem is ill-posed, if there is not enough information i.e., when an unknown function has to be inferred from insufficient information that specifies only feasible set of functions (GJM, 1996, p. 2). The ill-posed aspect may arise because the data is limited, partial or incomplete, i.e.: 1) number of unknown parameters exceeds the number of data points, 2) the data is mutually inconsistent.

Ill-conditioned problems are described in (GJM, 1996, pp. 127-128). In those cases, available data is enough to provide a well-posed problem, but the problem may still be ill-conditioned. For instance, there is significant multicollinearity in the data in a case of linearly dependent data, and solutions to seemingly well-posed problems may be undefined or non-unique. Furthermore, even if the estimates can be found, they may have high variance and they may be unstable. Traditionally, use of prior information and non-sample information has been a remedy for such situations.

An intuitive way to look at an ill-posed problem is to think of a system of $m$ equations and $n$ unknown. If $n = m$, then there exist a single, exact solution to that problem. If $m > n$, the equations can be thought of as data, and then traditional econometrics may be used to find statistical solution to the problem. However, if $m < n$, either external information must be delivered into the system, or the ME technique can be used in order to find the most probable solution to the system.

In practice, ME is a method for recovering a unkown probability distribution from given moment constraints. It was developed by Jaynes (1957a,b) using Shannon's (1948) definition of entropy as an information measure. Basically, if there is a system of equations, with less constraints (observations, equations) than unknowns (probabilities) to be discovered, the system has several solutions. For such a case, the least informative solution from a feasible set can be found, using Jaynes' ME-method. Jaynes' entropy is a measure of information. It is maximized, when there is the weakest set of assumptions (exogeneous structure) consistent with the observed data and with the stated model.

The entropy measure can be written as follows:

$$H(p) \equiv -\Sigma_{n=1}^{N} p_n ln(p_n) \equiv -p' ln(p), \tag{3.26}$$

where $p' \equiv [p_1, p_2, ..., p_N]$ is a discrete probability distribution. The purpose is to find the probabilities $p_N$, which maximize $H$, with respect to constraints, which can be thought of being a set of observations. The intuitive meaning behind the entropy measure is, according to Jaynes, that the entropy measure equals to "amount of uncertainty" of a probability distribution which is maximized, subject to constraints. This in turn forces the system to use all and only information what it has of the system, no more and no less.

In classical maximum entropy (ME) the unknowns are simplex-valued, in practice, often probability distributions, with constraints $p_r \geq 0$ for all $i$, and $\Sigma p_r = 1$. For real-valued unknowns generalized maximum entropy (GME) must be used. In GME real-valued variable is written as a summation of a product of two values, probability, $p_r$ and support parameter, $z_r$ i.e., $_j = \Sigma p_r z_r$. Support base $z_r, ..z_r$, is a vector of values in range of the expected value of the unknown, $_j$, where $r \geq 2$. Besides letting one to recover real-valued unknowns, GME formulation allows one to evaluate distribution of the probabilities, and the uncertainty of the data, or the sharpness of the inference. For more detailed discussion see GJM (1996, pp. 67-71).

In the entropy framework other knowledge besides the sample information, can be used in the system. When priors are used, the formulation is commonly called cross-entropy, CE. Furthermore, similarly as in the ME case, if the supports are used to recover real-valued unknowns, the procedure is called generalized cross entropy, CGE. In such a case Kullback's (1959) extension of the original ME formulation can be utilized:

$$CE(p, q) \equiv -\Sigma_{r=1}^{R} p_r ln(p_r/q_r) \equiv -p' ln(p) - p' ln(q), \tag{3.27}$$

where $q' \equiv [q_1, q_2, ..., q_N]$ resembles the non-sample information. Basically, $CE(p, q)$, measures the additional information in $p$ relative to $q$. It can be shown, that in a case, where $q$ is a discrete uniform distribution i.e., there is no additional information in the $q$, the latter formulation collapses to be the same as the one above, and thus, ME is a special case of the CE.

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